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FAIRBAIRN, Sir William, bart.
Two lectures on the construction of boilers and on boiler explosions.

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TWO LECTURES,

ON

THE CONSTRUCTION OF BOILERS,

AND ON

BOILER EXPLOSIONS,

WITH THE MEANS OF PREVENTION;

DELIVERED BEFORE THE LEEDS MECHANICS' INSTITUTION,

APRIL 23 AND 24, 1851:

ALSO A PAPER

ON THE

Consumption of Fuel and Prevention of Smoke,

READ BEFORE THE BRITISH ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE.

BY WILLIAM FAIRBAIRN, C.E., F.R.S.

LONDON:
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1851.

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ADVERTISEMENT.

The Two valuable Lectures, on "The Construction of the Boilers of Steam Engines," and "The Causes and Prevention of Explosions," were kindly delivered by their scientific Author, before the Leeds Mechanics' Institution, at the request of the Committee of the "Yorkshire Union of Mechanics' Institutes," in consequence of several disastrous accidents which had recently occurred. They are now published, by the Committee, in a cheap form, by the permission of the Author, along with a paper read by him before the "British Association for the Advancement of Science," on "The Consumption of Fuel and the Prevention of Smoke," in the hope that much practical benefit may result from the publication in this manufacturing district.

The best thanks of the Mechanics' Institutions are due to Mr. Fairbairn for his public-spirited conduct.

THE COMMITTEE OF THE YORKSHIRE UNION OF MECHANICS' INSTITUTES.

LEEDS, May, 1851.

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ON THE

CONSTRUCTION OF BOILERS.

LECTURE I.

The modifications of the Steam Engine which have been adopted since its introduction by Watt, three-quarters of a century ago, have been very numerous and varied; and although the progression in its applications and improvements has been most rapid and wonderful, we are still undecided as to the best form of its construction. Sound principles scientifically applied, and the gradually increasing excellence of our mechanical workshop, have enabled us to attain the great perfection which characterises the working parts of the modern steam engine. The steam engine itself may be regarded as a comparatively perfect machine, and I shall, therefore, confine my observations almost exclusively to that very important and necessary adjunct—*the Boiler*—which is the source of its power. With this limitation a very wide field of inquiry is opened out, and in the earliest steps of the investigation we become perplexed with the endless variety of forms and constructions which at different periods have been adopted by engineers, and which have never, unfortunately, received the same judicious attention that was paid, as I have already remarked, to the steam engine. This is an anomalous and much to be regretted fact, for the boiler, being the source of the motive power, is undoubtedly one of the most important parts of the whole machine. Upon its proper proportions and arrangements for the generation of steam depend the economy and regularity with which the engine can be worked, and upon its strength and excellence of workmanship depends the safety of the lives and property of those who come in contact with it. Regarding the steam engine as one of the most active agents in the extension of our prosperity, and in the civilization of the world, and seeing how it is mixed up with the daily duties and workings of society, the safety and efficiency of every part, and more especially the *boiler*, are subjects of national importance; and I feel gratified by being called upon to lay before you such knowledge and experience on this subject of deep interest as I myself possess.

I propose to consider the Boiler in its *Construction*, *Management*, *Security*, and *Economy*.

1st. As to the *Construction*. Here I shall have to go a little into detail in order to show, in construction, the absolute necessity there exists for adhering to form and other considerations, essential in the practice of mechanical engi-

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neers, in effecting the maximum of strength with the minimum of material. In boilers this is the more important, as any increase in the thickness of the plates obstructs the transmission of heat, and exposes the rivets as well as the plates to injury on the side exposed to the action of the furnace.

It has generally been supposed that the rolling of boiler plate iron gives to the sheets greater tenacity in the direction of their length than in that of their breadth; this is, however, not correct; as a series of experiments which I made some years since fully proves that there is no difference in the tensile strength of boiler plates whether torn asunder in the direction of the fibre, or across it. From five different sorts of iron the following results were obtained:—

Description of Iron.	Mean breaking weight in tons in the direction of the fibre.	Mean breaking weight in tons across the fibre.
Yorkshire Plates	25.77	27.49
Yorkshire Plates	22.76	26.37
Derbyshire Plates	21.68	18.65
Shropshire Plates	22.82	22.00
Staffordshire Plates	19.56	21.01
Mean	22.51	23.10

From this it appears that we may safely use iron plates in the construction of boilers in whatever direction may best suit the convenience of the maker. Next to the tenacity of the plates, comes the question of riveting, or the best and surest means of securing them together. On this part of the subject we have been widely astray, and it required some skill, and no inconsiderable attention, in conducting the experiments, to convince the unreflecting portion of the public, and even some of our boiler makers, that the riveted joints were not stronger than the plate itself. At first sight this would appear to be the case, but a moment's reflection will soon convince us to the contrary, as in punching holes along the edge of a plate it is obvious that the plate must be weakened to the extent of the sectional areas punched out, and that it is next to impossible, under the circumstances, to retain the same strength in the material after such diminution has been effected, as existed in the previously solid plate. This was clearly demonstrated by a series of experiments which took place some years since, and in which the strength of almost every description of riveted joints was determined by tearing them directly asunder. The results obtained from these experiments were conclusive as regards the relative strength of riveted joints and the solid plates. In two different kinds of joints—double and single riveted—the strengths were found to be, in the ratio of the plate, as the numbers 100, 70, and 56.

Assuming the strength of the plate to be	100
The strength of a double riveted joint would be, after allowing for the adhesion of the surfaces of the plate	70
And the strength of a single riveted joint	56

These proportions of the relative strengths of plates and joints may therefore, in practice, be safely taken as the standard value, in the construction of vessels required to be steam and water tight, and subjected to pressure varying from 10 lbs. to 100 lbs. on the square inch.

In the construction of boilers exposed to severe internal pressure, it is desirable to establish such forms, and so to dispose the material, as to apply the greatest strength in the direction of the greatest strain; and in order to accomplish this,

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it will be necessary to consider whether the same arrangement be required for all diameters, or whether the form as well as the disposition of the plates should not be changed. To determine these questions in cylindrical boilers, recourse must be had to experiment, or such deduction as may apply to any given case, and such as is founded upon unerring data derived from experimental research. On this head I am fortunate in having before me the calculations of Professor W. R. Johnson, of the Franklin Institute of America, whose inquiries into the strength of cylindrical boilers are of great value, and from which the following short abstract may be useful.

"1st. To know the force which tends to burst a cylindrical vessel in the longitudinal direction, or, in other words, to separate the *head* from the curved *sides;* we have only to consider the actual area of the head, and to multiply the units of *surface* by the number of units of *force* applied to each superficial unit. This will give the total *divellent* force in that direction.

"To counteract this, we have, or may be conceived to have, the tenacity of as many longitudinal bars as there are lineal units in the circumference of the cylinder. The united strength of these bars constitutes the total retaining or *quiescent* force, and at the moment when rupture is about to take place, the *divellent* and the quiescent forces must obviously be equal.

"2nd. To ascertain the amount of force which tends to rupture the cylinder along the curved side, or rather along the opposite sides, we may regard the pressure as applied through the whole breadth of the cylinder upon each lineal unit of the diameter. Hence the total amount of force which would tend to divide the cylinder in halves, by separating it along two lines, on opposite sides, would be represented by multiplying the diameter by the force exerted on each unit of surface, and this product by the length of the cylinder. But even without regarding the length, we may consider the force requisite to rupture a *single band* in the direction now supposed, and of one lineal unit in breadth; since it obviously makes no difference whether the cylinder be long or short, in respect to the ease or difficulty of separating the sides. The *divellent* force in this direction is therefore truly represented by the diameter multiplied by the pressure per *unit of surface.* The retaining or *quiescent* force, in the same direction, is only the strength or tenacity of the two opposite sides of the supposed bond. Here also at the moment when a rupture is about to occur, the divellent force must exactly equal the quiescent force."

Mr. Johnson then goes on to show, that as the diameter is increased, the product of the diameter and the force or pressure per unit of surface are increased in the same ratio. This truism I shall endeavour to prove; as also, that as the diameter of any cylindrical vessel is increased, the thickness of the metal must also be increased in the exact ratio of the increase of the diameter: the pressure, or, as Mr. Johnson calls it, the divellent force, being the same, when the diameter of a boiler is increased, it must be borne in mind that the area of the ends is also increased, not in the ratio of the diameter, but in the ratio of the square of the diameter; and it will be seen that instead of the force being doubled, as is the case in the direction of the diameter and circumference, it is quadrupled upon the ends, or, what is the same thing, a cylinder double the diameter of another cylinder, has to sustain four times the pressure in the longitudinal direction.

The retaining force or the thickness of the metal of a cylindrical boiler does not, however, increase in the same ratio as the area of the circle, but simply in the ratio of the diameter; consequently the thickness of the metal will require to be increased in the same ratio as the diameter is increased. From this it appears that the tendency to rupture by blowing out the ends of a cylindrical boiler will

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not be greater in this direction than it is in any other direction; we may, therefore, safely conclude, since we have seen that the tendency to rupture increases in both directions in the ratio of the diameter, that any deviation from that law, as regards the thickness of the plates, would not increase the strength of the boiler.

I have been led to these inquiries from the circumstance that Mr. Johnson appears to reason on the supposition that there are no joints in the plates, and that the tenacity of the iron is equal to 60,000 lbs.,—rather more than 26 tons to the square inch. Now we have shown by the results of the experiments already adduced, that ordinary boiler plates will not bear more than 23 tons to the square inch, and as nearly one-third of the material is punched out for the reception of the rivets, we must still further reduce the strength, and take 15 tons, or about 34,000 lbs.* on the square inch, as the tenacity of the material, or the pressure at which a boiler would burst.

This I should consider in practice as the maximum power of resistance of boiler plates in their riveted state, and I will now trouble you to follow me in a very concise and I trust not uninteresting investigation, as to the bearing powers of boilers, and the pressure at which they can be worked with safety.

It has been stated that the strength of cylindrical boilers, when taken in the direction of their circumference, is in the ratio of their diameters, and when taken in the direction of the ends, as the squares of the diameters,—a proposition which it will not be difficult to demonstrate as applicable to every description of boiler of the cylindrical form. It will be seen, however, that the strain is not exactly the same in every direction, and that there is actually less upon the material in the longitudinal direction, than there is upon the circumference. For example, let us take two boilers, one three feet diameter and the other six feet, and suppose each to be subject to a pressure of 40 lbs. on the square inch. In this condition, it is evident that the area or number of square inches in the end of a three feet boiler is to that of the area of the six feet boiler as 1 to 4; and by a common process of arithmetic it will be found that the edges of the plates forming the cylindrical part of the three feet boiler is subject (at 40 lbs. on the square inch) to a pressure of 40,712 lbs.—upwards of 18 tons; whereas the plates of the six feet boiler have to sustain a pressure of 162,848 lbs., or 72 tons, which is quadruple the force to which the boiler only one-half the diameter is exposed; and the circumferences being only as two to one, there is necessarily double the strain upon the cylindrical plates of the large boiler. Now this is not the case with the other parts of the boiler, as the circumference of a cylinder increases only in the ratio of the diameter, consequently the pressure, instead of being increased in the ratio of the squares of the diameter, as shown in the ends, is only doubled, the circumference of the six feet boiler being twice that of the three feet boiler.

Let us, for the sake of illustration, suppose the two cylindrical boilers, such as we have described, to be divided into a series of hoops of one inch in width; and, taking one of these hoops in the three feet boiler, we shall find it exposed at a pressure of 40 lbs. on the square inch, to a force of 1,440 lbs., acting on each side of a line drawn through the axis of a cylinder 36 inches diameter, and 1 inch in depth, and which line forms the diameter of the circle. Now this force causes a strain upon the points *a a* in the direction of the arrows in the

* By experiment it is found that the strength of the riveted joints of boilers is only about one-half the strength of the plate itself; but taking into consideration the crossing of the joints, 34,000 lbs. may reasonably be taken as the tenacity of the riveted plates, or the bursting pressure of a cylindrical boiler.

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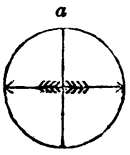
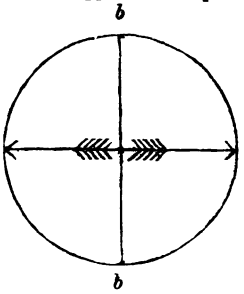
annexed diagram of the three feet circle of 720 lbs., and assuming the pressure



to be increased till the force becomes equal to the tenacity or retaining powers of the iron at *a a*, it is evident, in this state of the equilibrium of the two forces, that the least preponderance on the side of the internal pressure would insure fracture. And, suppose we take the plates of which the boiler is composed at one quarter of an inch thick, and the ultimate strength at 34,000 lbs. on the square inch, we shall have $\frac{34,000}{36 \times 2}$=472 lbs. per square inch, as the bursting pressure of the boiler. Again, as the forces in this direction are not as the squares, but simply as the diameters, it is clear that at 40 lbs. on the square inch, we have in a hoop an inch in depth, or that portion of a cylinder whose diameter is six feet, exactly double the force applied to the points *b b*, which was acting on



the points *a a*, in the diameter of three feet. Now, assuming the plates to be a quarter of an inch thick, as in the three feet boiler, it follows, if the forces at the same pressure be doubled in the large cylinder, that the thickness of the plates must also be doubled in order to sustain the same pressure with equal security; or what is the same thing, the six feet boiler must be worked at half the pressure, in order to insure the same degree of safety as attained in the three feet boiler at double the pressure. From these facts it may be useful to know, that boilers having increased dimensions should also have increased strength in the ratio of their diameters; or, in other words, the plates of a six feet boiler should be double the thickness of the plates of a three feet boiler, and so on in proportion as the diameter is increased.

The relative power of force applied to cylinders of different diameters becomes more strikingly apparent when we reduce them to their equivalents of strain per square inch, as applied to the ends and circumference of the boiler respectively. In the three feet boiler, working at 40 lbs. pressure, we have a force equal to 720 lbs. upon an inch width of plate, and one quarter of an inch thick, or 720 by 4 = 2,880 lbs., the force per square inch upon every point of the circumference of the boiler.

Let us now compare this with the actual strength of the riveted plates themselves, which taken as before at 34,000 lbs. on the square inch, we arrive at the ratio of pressure as applied to the strength of the circumference as 2,880 to 34,000, nearly as 1 to 12, or 472 lbs. per square inch, as the ultimate strength of the riveted plates.

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These deductions appear to be true in every case as regards the resisting powers of cylindrical boilers, to a force radiating in every direction from the axis towards the circumference; but the same reasoning is, however, not maintained when applied to the ends, or, to speak technically, to the angle iron and riveting where the ends are attached to the circumference. Now, to prove this, let us take the three feet boiler, where we have 113 inches in the circumference, and upon this circular line of connection we have, at 40 lbs. to the square inch, to sustain a pressure of 18 tons, which is equal to a strain of 360 lbs. acting longitudinally upon every inch of the circumference. Apply the same force to a six feet boiler, with a circumference or line of connection equal to 226 inches, and we shall find it exposed to exactly four times the force, or 72 tons; but in this case it must be borne in mind that the circumference is doubled, and consequently the strain, instead of being in the quadruple ratio, is only doubled, or a force equal to 720 lbs. acting longitudinally as before upon every inch of the circumference of the boiler. From these facts we come to the conclusion that the strength of cylindrical boilers is in the ratio of their diameters if taken in the line of curvature, and as the squares of the diameters as applied to the ends or their sectional area; and that all descriptions of cylindrical tubes, to bear the same pressure, must be increased in strength in the direction of their circumference simply as their diameters, and in the direction of the ends as the squares of the diameters.

Again, if we refer to the comparative merits of the plates composing cylindrical vessels subjected to internal pressure, they will be found in this anomalous condition, that the strength in their longitudinal direction is twice that of the plates in the curvilinear direction. This appears by a comparison of the two forces, wherein we have shown that the ends of the three feet boiler, at 40 lbs. internal pressure, sustain 360 lbs. of longitudinal strain upon each inch of a plate a quarter of an inch thick; whereas the same thickness of plates have to bear in the curvilinear direction a strain of 720 lbs. This difference of strain is a difficulty not easily overcome, and all that we can accomplish in this case will be to exercise a sound judgment in crossing the joints, in the quality of the workmanship, and the distribution of the material. For the attainment of these objects, the following table, which exhibits the proportionate strength of cylindrical boilers from three to eight feet in diameter, may be useful.

TABLE of equal strengths in Cylindrical Boilers from three to eight feet diameter, showing the thickness of metal in each respectively, at a pressure of 450 lbs. to the square inch:—

Diameter of Boilers.		Bursting pressure — equivalent to the ultimate strength of the riveted joint—as deduced from experiment. 34,000 lbs. to the square inch.	Thickness of the plates in decimal parts of an inch.
Feet.	Inches.		
3	0	450 lbs.	.250
3	6		.291
4	0		.333
4	6		.376
5	0		.416
5	6		.458
6	0		.500
6	6		.541
7	0		.583
7	6		.625
8	0		.666

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Boilers of the simple form, and without internal flues, are subjected only to one species of strain; but those constructed with internal flues are exposed to the same tensile force which pervades the simple form; and, further, to the force of compression which tends to collapse, or crush the material of the internal flues. In the cylindrical boiler with round flues, the forces are diverging from the central axis as regards the outer shell, and converging as applied to every separate flue which the boiler contains.

These two forces in a steam boiler are in constant operation; the tendency of the one being to tear up the external plates and force out the ends, and the other to destroy the form and to force the material into the central area of the flues. These two forces operate widely different upon the resisting powers of the boiler, which, taken in the direction of its exterior envelope, has to resist a tensile strain operating in every direction from within, and the internal flues, acting as an arch, offer a powerful resistance to compression from without. It might be instructive as well as interesting to exhibit the nature of these powers, and determine the law by which vessels of this description are retained in shape; but this can only be done by experiment, and as these experiments would have to be conducted upon a large scale, and with great accuracy, in order to arrive at satisfactory results, we must abandon the idea for the present, and content ourselves with such information as we already possess. At some future period I may possibly devote my attention to this subject; it is one of great importance, and a series of well-conducted experiments would, I make no doubt, supply valuable data in the varied requirements of boiler construction, and their comparative powers of resistance to the united force of tension and compression.

From the existing state of our knowledge, we must rest satisfied with the fact, that the resisting powers of cylindrical flues to compression will be directly as their diameters; and we may therefore conclude that a circular flue, eighteen inches in diameter, will resist double the pressure of one three feet diameter. Hence it follows that the resistance of wrought iron plates of the circular form is to the force of compression as their diameters—the same, but with greatly diminished powers, as compared with the resistance of wrought iron cylindrical plates to tension.

To show the amount of strain upon a high pressure boiler 30 feet long, 6 feet diameter, having two centre flues, each 2 feet 3 inches diameter, working at a pressure of 50 lbs. on the square inch, we have only to multiply the number of square feet of surface, 1,030, exposed to pressure, by 321, and we have the force of 3,319 tons, which a boiler of these dimensions has to sustain. I mention this to show that the statistics of pressure, when worked out, are not only curious in themselves, but instructive as regards a knowledge of the retaining powers of vessels so extensively used, and on which the bread of thousands depends. To pursue the subject a little further, let us suppose the pressure to be at 450 lbs. on the square inch, which a well constructed boiler of this description will bear before it bursts, and we have the enormous force of 29,871, or nearly 30,000 tons bottled up within a cylinder 30 feet long, and 6 feet diameter.

This is, however, inconsiderable when compared with the locomotive, and some marine boilers, which, from the number of tubes, present a much larger extent of surface to pressure. Locomotive engines are usually worked at 80 to 100 lbs. on the inch; and, taking one of the usual construction, we shall find at 100 lbs. on the inch that it rushes forward on the rail with a pent up force, within its interior, of nearly 60,000 tons, which is rather increased than diminished at an accelerated speed.

In a stationary boiler charged with steam at a given pressure, it is evident that

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the forces are in perfect equilibrium, and the strain being the same in all directions, there will be no tendency to motion. Supposing, however, this equilibrium to be destroyed by accumulative pressure till rupture ensues, it then follows that the forces in one direction having ceased, the others in an opposite direction being active, would project the boiler from its seat with a force equal to that which is discharged through the orifice of rupture. The direction of motion would depend upon the position of the ruptured part. If in the line of the centre of gravity, motion would ensue in that direction; if out of that line, an oblique or rotatory motion round the centre of gravity would be the result.

The velocity or quantity of motion produced in one direction would be equal to the intensity or quantity lost; and the velocity with which the body would move would be in the ratio of the impulsive force, or the quantity lost. Therefore, the quantity of motion gained by an exploded boiler in one direction, will be as its weight and the quantity lost in that direction. These definitions are, however, more in the province of the mathematician, and may easily be computed from well known formula on the laws of motion.

We now come to the rectangular forms, or flat surfaces, which are not so well calculated to resist pressure. Of these we may instance the fire-box of the locomotive boiler, the sides and flues of marine boilers,—the latter of which, by the bye, are now superseded by those of the tubular form,—and the flat ends of the cylindrical boilers, and others of weaker construction.

The locomotive boiler is frequently worked up to a pressure of 120 lbs. on the square inch, and at times, when rising steep gradients, I have known the steam nearly as high as 200 lbs. on the inch. In a locomotive boiler subject to such an enormous working pressure, it requires the utmost care and attention on the part of the engineer to satisfy himself that the flat surfaces of the fire-box are capable of resisting that pressure, and that every part of the boiler is so nearly balanced in its powers of resistance as that when one part is at the point of rupture, every other part is on the point of yielding to the same uniform force. This appears to be an important consideration in mechanical constructions of every kind, as any material applied for the security of one part of a vessel subject to uniform pressure, whilst another part is left weak, is so much material thrown away; and in stationary boilers, or in moving bodies, such as locomotive engines and steam vessels, it is absolutely injurious, at least so far as the parts are disproportionate to each other, and the extra weight, when maintained in motion, becomes an expensive and unwieldy encumbrance. A knowledge of the strength of the materials used, judicious care, and the exercise of sound judgment in its distribution, are therefore some of the most essential qualifications of the practical engineer. Our limited knowledge, and defective principles of construction, are manifest from the numerous abortions which exist, and although I am free to communicate all that I know on the subject, I nevertheless find myself deficient in many of the requirements necessary for the attainment of sound principles of construction.

Reverting to the question more immediately under consideration, it is, however, essential to give the requisite security to those parts which, if left unsupported, would involve the public as well as ourselves in the greatest jeopardy.

The greater portion of the fire boxes of locomotive boilers, as before noticed, have the rectangular form, and in order to economise heat and give space for the furnace, it becomes necessary to have an interior and exterior shell. That which contains the furnace is generally made of copper, firmly united by rivets, and the exterior shell, which covers the fire-box, is made of iron and united by rivets, in the same way as the copper fire-box. Now these plates would of themselves

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be totally inadequate, unless supported by riveted stays, to sustain the pressure. In fact, with one-tenth the strain, the copper fire-box would be forced inwards upon the furnace, and the external shell bulged outwards, and with every change of force these two flat surfaces would move backwards and forwards, like the sides of an inflated bladder, at the point of rupture. To prevent this, and give the large flat surfaces an approximate degree of strength with the other parts of the boiler, wrought iron or copper stays, one inch thick, are introduced; they are first screwed into the iron and copper on both sides to prevent leakage, and then firmly riveted to the interior and exterior plates. These stays are about six inches asunder, forming a series of squares, and each of them will resist a strain of about fifteen tons before it breaks.

Let us now suppose the greatest pressure contained in the boiler to be 200 lbs. on the square inch, and we have $6 \times 6 \times 200 = 7{,}200$ lbs., or $3\frac{1}{4}$ tons, the force applied to a square of 36 inches. Now as these squares are supported by four stays, each capable of sustaining fifteen tons, we have $4 \times 15 = 60$ tons, as the resisting powers of the stays, but the pressure is not divided amongst all the four, but each stay has to sustain that pressure, consequently the ratio of strength to the pressure will be as $4\frac{1}{2}$ to 1 nearly, which is a very fair proportion for the resisting power of that part.

We have treated of the sides, but the top of the fire-box and the ends have also to be protected, and there being no plate but the circular top of the boiler from which to attach stays, it has been found more convenient and equally advantageous to secure those parts by a series of strong wrought iron bars, from which the roof of the fire-box is suspended, and which effectually prevent it from being forced down upon the fire. It will not be necessary to go into the calculations of those parts; they are, when riveted to the dome or roof, of sufficient strength to resist a pressure of 300 to 400 lbs. on the square inch. This is, however, generally speaking, the weakest part of the boiler, with the exception, probably, of the flat end above the tubes in the smoke-box, if not carefully stayed.

In the flat ends of cylindrical boilers, and those of the marine principle, the same rule applies as regards construction, and a due proportion of the parts, as in those of the locomotive boilers, must be closely adhered to. Every description of boiler used in manufactories, or on board of steamers, should, in my opinion, be constructed to a bursting pressure of 400 to 500 lbs. on the square inch; and locomotive engine boilers, which are subjected to a much severer duty, to a bursting pressure of 600 to 700 lbs.

It now only remains for me to state that internal flues, such as contain the furnace in the interior of the boiler, should be kept as near as possible to the cylindrical form: and as wrought iron will yield to a force tending to crush it of about one-half of what would tear it asunder, the flues should in no case exceed one-half the diameter of the boiler; and with the same thickness of plates they may be considered equally safe with the other parts. But the force of compression is so different to that of tension, that I should advise the diameter of the internal flues to be in the ratio of 1 to $2\frac{1}{2}$, instead of 1 to 2, of the diameter of the boiler.

I will not trouble you with a description of the haycock, hemispherical, and waggon-shaped boilers; they are all bad as respects their powers of resistance, and ought to be entirely exploded; I shall congratulate the public when they disappear from the list of those constructions having the confidence of the public, and the consideration of the man of science or the practical engineer.

In conclusion, I have to recommend attention to a few simple rules, which, if

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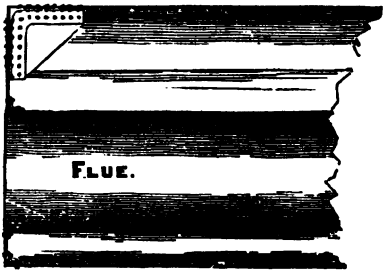
carefully observed, will lead to the most satisfactory results. To construct boilers as nearly as possible of maximum strength, I have already observed they should be of the cylindrical form; and where flat ends are used they should be composed of plates one-half thicker than those which form the circumference. The flues, if two in number, to be of the same thickness as the exterior shell; and the flat ends to be carefully stayed with gussets of triangular plates and angle iron, firmly connecting them with the circumference, as per annexed sketch. The use of



gussets I earnestly recommend, as being infinitely superior to, and more certain in their action and retaining powers than stay rods. Gussets, when used, should be placed in lines diverging from the centre of the boiler, and made as long as the position of the flues and other circumstances in the construction will admit. They are of great value in retaining the ends in shape, and may safely be relied upon as imparting an equality of strength to every part of the structure. With these observations, I would direct attention to the facts I have endeavoured to inculcate. You will, I am persuaded, find them useful; and I trust the objects contemplated by the Committee of your valuable Institution will be fully attained, in the acquisition of greater security and a more perfect principle of construction.

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ON BOILER EXPLOSIONS.

LECTURE II.

In a former lecture I endeavoured to explain the principles on which Boilers should be constructed, and the laws which govern the strength and other properties of these important vessels. The subject of construction is one of vast importance, and those forms which give the greatest security with the least quantity of material, may be considered as the safest examples for imitation—the true elements of construction. Boilers, of all other vessels, require, in the variety of their conditions, shapes, and dimensions, the head of the philosopher as well as the hands of the mechanic. They contain, within comparatively narrow bounds, a force which, if properly governed, will propel the largest and most stately vessel against wind and tide; perform the work of a thousand hands, and drive a hundred cars loaded with hundreds of tons, at the speed of the swiftest race horse, from one extremity of the kingdom to the other. They do all this and more; they impart heat and comfort to our dwellings,—are essential for the requirements of our domestic arrangements,—and under the control of judicious management, will advance the interests of commerce, and contribute to the enjoyments of civilized existence.

Reverse the picture, and entrust the construction and management to the hands of incapacity and ignorance, or the reckless folly and hardihood of fancied security, and death and destruction follow as a result. When the mischief is done, we then begin to guess at the causes, and to lament the inconsiderate confidence which led to the employment of incompetency, and all those errors of judgment which invariably present themselves, not before, but after the event. How often do we hear of the most lamentable accidents terminating in the destruction of life and property, and how often do we lament (when too late) the causes which led to those frightful catastrophes! All these accidents might be prevented, and, instead of using steam, which we now do in our manufactories, at a pressure of 5 to 20 lbs. on the square inch, we may with equal safety use it, and enjoy the advantage of its superior economy, at 60 lbs. on the inch. It shall be my duty to point out how this may be accomplished, and I hope in these endeavours to have the support of every well wisher for increased security to the public, and enlarged economy in the varied requirements of the use of steam.

Before I attempt a solution of this difficult question, I would first direct attention to a few facts which bear more directly upon the question now at issue.

Various notions are entertained as to the causes of boiler explosions, and scientific men are not always agreed as to whether they arise from excessive pressure due to the accumulation of heat, or to some other cause, such as the explosion of hydrogen gas, generated by the decomposition of water suddenly

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thrown on heated plates, of which we have an exceedingly indefinite conception. That of the decomposition of water is, I believe, a somewhat prevalent opinion, but I apprehend it cannot be the invariable cause, inasmuch as in that case we must assume the boiler to be nearly empty of water, and the plates over the furnace red hot.

It is not unreasonable to suppose that a force of such sudden origin, and so immediate and destructive in its effects, should suggest the presence of an explosive mixture; but I think it will be difficult, if not impossible, to account for the accumulation of a sufficient quantity of hydrogen, without the presence of oxygen and other gases, in their due proportions, to form an explosive compound. Now as these equivalents cannot be generated all at once by the simple decomposition of water, (admitting for the moment that the water is decomposed), we must look for some other cause for the fatal and destructive accidents which of late years have become so prevalent.

In treating of this subject, I hope to show not only what are the probable causes of explosions, but, what appears equally important, what are not the causes. So many theories (some of them exceedingly problematical) have been brought forward on the occasion of disastrous explosions, that it requires the utmost care and attention to circumstances before they are generally admitted. To acquire satisfactory evidence as to the precise condition of the boiler and furnace before an explosion, is next to impossible, as most frequently the parties in charge, and from whose mismanagement and neglect we may, in many cases, date the origin of the occurrence, are the first to become the victims of their own indiscretion, and we can only judge from the havoc and devastation that ensues as to the immediate cause of the event.

From this it follows that, in many of the explosions on record, few, if any, of the real circumstances of the case are made known, and we are left to draw conclusions from the appearances of the ruptured parts, and the terrific consequences which too frequently follow as a result. This want of evidence as to the precise condition of a boiler, with all its valves and mountings, preceding an explosion, is much to be regretted, as it causes a degree of mystery to surround the whole transaction; and the vague and sometimes inaccurate testimony of witnesses but too often baffles all attempts at research, and creates additional cause of alarm to all those exposed to the occurrence of similar dangers.

In the discussion of this subject I shall, however, endeavour to trace, from a number of examples in which I have been personally engaged, and from others which have come to my knowledge, the causes which have led to these disastrous effects; and provided I am successful in the discovery of the true origin of the majority of those occurrences, we shall have less difficulty in devising and applying the necessary remedies for their prevention.

In my attempts to ascertain facts by a course of reasoning which I shall have to follow in this investigation, I wish it to be understood that it is not my intention to raise doubts and fears in the public mind, calculated to arrest the progress of commercial enterprise, or to cripple the energies of mechanical skill. On the contrary, I am most anxious to promote the advancement of the useful arts, to increase our confidence in the application of increased pressure, and to secure within moderate bounds the economical and useful employment of one of the most powerful agents ever known in the history of practical science. My object in this inquiry will, therefore, be to enlarge our sphere of action by a more comprehensive knowledge of the subject on which it treats; to induce greater caution along with improved construction; and to insure confidence in all those requirements essential to the public security.

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For the attainment of these objects it will be necessary to divide the subject into the following heads:—

1st. Boiler explosions arising from accumulated internal pressure.
2nd. Explosions from deficiency of water.
3rd. Explosions produced from collapse.
4th. Explosions from defective construction.
5th. Explosions arising from mismanagement or ignorance; and
6th. The remedies applicable for the prevention of these accidents.

1st. *Boiler explosions arising from accumulated internal pressure.*

In nine cases out of ten a continuous increasing pressure of steam, without the means of escape, is probably the immediate cause of explosion; in some instances it arises from deficiency of water, but accidents of this kind are comparatively few in number, as we often find, in tracing the causes, that they have their origin in undue pressure, emanating from progressive accumulation of steam of great force and density. Let us take an example, and we shall find that a boiler under the influence of a furnace in active combustion will generate an immense quantity of steam; and unless this is carried off by the safety-valve or the usual channels when so generated, the greatest danger may be apprehended by the continuous increase of pressure that is taking place within the boiler. Suppose that, from some cause, the steam thus accumulated does not escape with the same rapidity with which it is generated,—that the safety-valves are either inadequate to the full discharge of the surplus steam, or that they are entirely inoperative, which is sometimes the case,—and we have at once the clue to the injurious consequences which, as a matter of fact, are sure to follow. The event may be procrastinated, and repeated trials of the antagonistic forces from within, and the resistance of the plates from without, may occur without any apparent danger, but these experiments often repeated will at length injure the resisting powers of the material, and the ultimatum will be the arrival of the fatal moment when the balance of the two forces is destroyed, and explosion ensues. How very often do we find this to be the true cause of accidents arising from extreme internal pressure, and how very easily these accidents might be avoided by the attachment of proper safety valves to allow the steam to escape, and relieve the boiler of those severe trials which ultimately lead to destruction! If a boiler whose generative power is equal to 100, be worked at a pressure of 10 lbs. on the square inch, the area of the safety valves should also be equal to 100, in order to prevent a continuous increase of pressure; or in case of the adhesion of any of the valves, it is desirable that their areas should, collectively, be equal to 100. If two or more valves are used, 100 or 120 would then be the measure of outlet.* Under these precautions, and with a boiler so constructed, the risk of accident is greatly diminished; and, provided one of the valves is kept in working order, beyond the reach of interference by the engineer, *or any other person*, we may venture to assume that the means of escape are at hand, irrespective of the temporary stoppage of the usual channels for carrying off the steam.

So many accidents have occurred from this cause—the defective state of the safety valves—that I must request attention whilst I enumerate a few of the most prominent cases that have come before me. In the year 1845 a tremendous explosion took place at a cotton mill in Bolton. The boilers, three in number, were situated under the mill, and from the unequal capacity and imperfect state

* This may be stated in other words, viz., that the generative powers of a boiler being equal to a given number of square inches of area, say 50, the area of the safety valve should also be 50.

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of the safety valves, (as they were probably fast,) a terrific explosion of the weakest boiler took place, which tore up the plates along the bottom, and, the steam having no outlet at the top, not only burst out the end next the furnace, demolishing the building in that direction, but, tearing up the top on the opposite side, the boiler was projected upwards in an oblique direction, carrying the floors, walls, and every other obstruction before it; ultimately it lodged itself across the railway at some distance from the building. Looking at the disastrous consequences of this accident, and the number of persons (from 16 to 18) who lost their lives on the occasion, it became a subject of deep interest to the community that a close investigation should immediately be instituted, and a recommendation followed that every precaution should be used in the construction as well as the management of boilers.

The next fatal occurrence on record in this district was a boiler at Ashton-under-Lyne, which exploded under similar circumstances, namely, from excessive interior pressure, when four or five lives were lost; and again at Hyde, where a similar accident occurred from the same cause, which was afterwards traced to the insane act of the stoker or engineer, who prevented all means for the steam to escape by tying down the safety valve.

There was a boiler explosion at Malaga, in Spain, some years since, and my reason for noticing it in this place is to show that explosions may be apprehended from other causes than those enumerated in the divisions of this inquiry, and one of these is *incrustation*. Dr. Ritterbrandt says, in a paper read before the Institution of Civil Engineers, by an eminent chemist, Mr. West—"That a sudden evolution of steam under circumstances of incrustation is no uncommon occurrence." In several instances I have known this to be the case, particularly in marine boilers, where the incrustation from salt water becomes a serious grievance, either as regards the duration of the boiler, or the economy of fuel.

If it were supposed, as Dr. Ritterbrandt observes, that the boiler was incrusted to the extent of half an inch, it would at once be seen that nothing was more easy than to heat the boiler strongly, even to a red heat, without the immediate contact of water. Under these circumstances, the hardened deposits being firmly attached to the plates, and forming an imperfect conductor of heat, would tend greatly to increase the temperature of the iron, and the difference of temperature thus induced between the iron and the incrustation, and the greater expansibility of the iron, would cause the incrustation to separate from the plates, and the water rushing in between them, would generate a considerable charge of highly elastic steam, and thus endanger the security of the boiler.

These phenomena were singularly exemplified in the Malaga explosion, which is thus described by Mr. Hick:—"I have ascertained that a very thick incrustation of salt was formed on the lower part of the boiler, immediately over the fire, and so far as it extended the plates appear to have been red hot, being thereby much weakened, and hence the explosion. The ordinary working pressure of the boiler is 130 lbs. per square inch, and perhaps at the time of the explosion very much above that pressure, as there was only one small safety valve of two and a-half inches diameter. The boiler was only two feet six inches diameter, and twenty feet long."

Incrustation, exclusive of being dangerous, is attended with great expense and injury to the boiler by its removal. In the case of the transatlantic, oriental, or other long sea-going vessels, even after the use of brine-pumps, blowing out, &c., a very large amount of incrustation is formed, and considerable sums of money are expended each voyage to remove it.

Other explosions of a more recent date are those which occurred at Bradford

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and Halifax. They are still fresh in the recollection of the public mind, and are so well known as not to require notice in this place.

I cannot, however, leave this part of the subject without reverting to an accident which occurred on the Lancashire and Yorkshire Railway, which had its origin in the same cause—excessive internal pressure. This accident is the more peculiar as it led to a long mathematical disquisition as to the nature of the forces which produced results at once curious and interesting. The conclusions which I arrived at, although *practically right, were, however, considered by some mathematically wrong*, as they were firmly combatted by several eminent mathematicians; but notwithstanding the number of algebraic formulas, and the learned discussions of my friends on that occasion, I have been unable to change the opinions I then formed, for others more conclusive.

The accident here alluded to occurred to the "Irk" locomotive engine, which, in February, 1845, blew up and killed the driver, stoker, and another person who was standing near the spot at the time. A great difference of opinion as to the cause of this accident was prevalent in the minds of those who witnessed the explosion, some attributing it to a crack in the copper fire box, and others to the weakness of the stays over the top. Neither of these opinions was, however, correct, as it was afterwards demonstrated that the material was not only entirely free from cracks and flaws, but the stays were proved sufficient to resist a pressure of 150 to 200 lbs. on the square inch. The true cause was afterwards ascertained to arise from the fastening down of the safety valve of the engine, (an active fire being in operation under the boiler at the time), which was under the shed, with the steam up, ready to start with the early morning train. The effect of this was the forcing down of the top of the copper fire-box upon the blazing embers of the furnace, which, acting upon the principle of the rocket, elevated the boiler and engine of 20 tons weight to a height of 30 feet, which, in its ascent, made a summerset in the air, passed through the roof of the shed, and ultimately landed at a distance of 60 yards from its original position. The question which excited most interest, was the absolute force required to fracture the fire-box, its peculiar properties when once liberated, and the elastic or continuous powers in operation, which forced the engine from its place to an elevation of 30 feet from the position in which it stood. An elaborate mathematical discussion ensued relative to the nature of these forces, which ended in the opinion that a pressure sufficient to rupture the fire-box, was, by its continuous action, sufficient to elevate the boiler and produce the results which followed. Another reason was assigned, namely, that an accumulated force of elastic vapour, at a high temperature, with no outlet through the valves, having suddenly burst upon the glowing embers of the furnace, would charge the products of combustion with their equivalents of oxygen, and hence explosion followed. Whether one or both of these two causes were in operation is probably difficult to determine; at all events, we have in many instances precisely the same results produced from similar causes, and unless greater precaution is used in the prevention of excessive pressure, we may naturally expect a repetition of the same fatal consequences.

The preventives against accidents of this kind are, well constructed boilers of the strongest form, and duly proportioned safety valves; one under the immediate control of the engineer, and the other, as a reserve, under the keeping of some competent authority.

2nd. Explosions from deficiency of water.

This division of the subject requires the utmost care and attention, as the circumstance of boilers being short of water is no unusual occurrence. Im-

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minent danger frequently arises from this cause; and it cannot be too forcibly impressed upon the minds of engineers, that there is no part of the apparatus constituting the mountings of a boiler which require greater attention—probably the safety valves not excepted—than that which supplies it with water. A well constructed pump, and self-acting feeders, when boilers are worked at a low pressure, are indispensable; and where the latter cannot be applied, the glass tubular gauge, steam, and water cocks must have more than ordinary attention.

In a properly constructed boiler every part of the metal exposed to the direct action of the fire should be in immediate contact with the water, and when proper provision is made to maintain the water at a sufficient height above the part of the plates so exposed, accidents can never occur from this cause.

Should the water, however, get low from defects in the pump, or any stoppage of the regulating feed valves, and the plates over the furnace become red hot, we then risk the bursting of the boiler, even at the ordinary working pressure. We have no occasion, under such circumstances, to search for another cause, from the fact that the material when raised to a red heat has lost about five-sixths of its strength, and a force of less than one-sixth will be found amply sufficient to bear down the plates direct upon the fire, or to burst the boiler.

When a boiler becomes short of water, the first, and perhaps the most natural action, is to run to the feed valve, and pull it wide open. This certainly remedies the deficiency, but increases the danger, by suddenly pouring upon the incandescent plates a large body of water, which, coming in contact with a reservoir of intense heat, is calculated to produce highly elastic steam. This has been hitherto controverted by several eminent chemists and philosophers; but I make no doubt such is the case, unless the pressure has forced the plates into a concave shape, which for a time would retard the evaporization of the water when suddenly thrown upon them. Some curious experimental facts have been elicited on this subject, and those of M. Boutigny, and Professor Bowman, of King's College, London, show that a small quantity of water projected upon a hot plate does not touch it; that it forms itself into a globule surrounded with a thin film, and rolls about upon the plate without the least appearance of evaporation. A repulsive action takes place, and these phenomena are explained upon the supposition that the spheroid has a perfectly reflecting surface, and consequently the heat of the incandescent plate is reflected back upon it. What is, however, the most extraordinary in these experiments, is the fact that the globule, whilst rolling upon a red hot plate, never exceeds a temperature of about 204° of Fahrenheit; and in order to produce ebullition, it is necessary to cool the plate until the water begins to boil, when it is rapidly dissipated in steam.

The experiments by the committee of the Franklin Institute on this subject, give some interesting and useful results. That committee found that the temperature at which clean iron vaporized drops of water, was 334° Fahrenheit. The development of a repulsive force which I have endeavoured to describe was, however, so rapid above that temperature, that drops which required but one second of time to disappear at the temperature of maximum vaporization, required 152 seconds when the metal was heated to 395° of Fahrenheit. The committee go on to state that—"One ounce of water introduced into an iron bowl three-sixteenths of an inch thick, and supplied with heat by an oil-bath, at the temperature of 546°, was vaporized in fifteen seconds, while at the initial temperature of 507°, that of the most rapid evaporization was thirteen seconds."

The cooling effect of the metal is here strikingly exemplified by the increased rapidity of the evaporization, which at a reduced temperature of 38° is effected in thirteen instead of fifteen seconds.

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This does not, however, hold good in every case, as an increased quantity of water, say from one-eighth of an ounce to two ounces, thrown upon heated plates, raised the temperature of vaporization from 460° to 600° Fahrenheit: thus clearly showing that the time required for the generation of explosive steam under these circumstances is attended with danger; and it may be doubted whether the ordinary safety valves may not be wholly inadequate for its escape.

Numerous examples may be quoted to show that explosions from deficiency of water, although less frequent than those arising from undue pressure, are by no means uncommon. They are nevertheless comparatively fewer in number, and the preventives are good pumps, self-acting feeders, (when they can be applied), and all those conveniences, such as water cocks, water gauges, floats, alarms, and other indicators of the loss and reduction of water in the boiler.

3rd. Explosions produced from collapse.

Accidents from this cause can scarcely be called explosions, as they arise, not from internal force which bursts the boiler, but from the sudden action of a vacuum within it. In high pressure boilers, from their superior strength and circular form, these accidents seldom occur, and the low pressure boiler is effectually guarded against it by a valve which opens inwards by the pressure of the atmosphere whenever a vacuum occurs. In some cases a collapse of the internal flues of boilers has been known to take place, from a partial vacuum within, which, united to the pressure of the steam, has forced down the top and sides of the flue, and with fatal effect discharged the contents of the boiler into the ash-pit, and destroyed and scalded everything before it. A circumstance of this kind occurred on the Thames on board the steamer *Victoria*, some years since, when a number of persons lost their lives, and serious injury was sustained in all parts of the vessel within reach of the steam. This accident could not, however, be called an explosion, but a collapse of the internal flues, which were of large dimensions, and the consequent discharge of large quantities of steam and water into the space occupied by the engines.

One or two cases which bear more directly on this point are, however, on record, and one of them, which took place in the Mold mines, in Flintshire, was attended with explosion. The particulars, as given by Mr. John Taylor, will be found circumstantially recorded in the first volume of the *Philosophical Magazine*. This occurrence seems to prove that rarefaction produced in the flues of a high pressure boiler may determine an explosion. The boiler which exploded belonged to a set of three feeding the same engine; the fuel used was bituminous coal. The furnace doors of all three of the boilers had been opened, and the dampers of two had been closed, when a gust of flame was seen to issue from the mouth of the furnace of these latter, and was immediately followed by an explosion. The interior flue of this boiler was flattened from the sides, the flue and shell of the boiler remaining in their places, and the safety valve upon the latter not being injured.

Other similar cases of collapse might be stated, but as most of them have been attended by a defective supply of water in the boiler, the plates over the fire having become heated, they can scarcely be included in the category of this class of accidents, and more properly belong to those of which we have just treated,—explosions from a deficiency of water in the boiler.

It is, nevertheless, necessary to observe, that cases of collapse should be carefully guarded against, as the great source of danger is in the escape of hot water, which, with the steam generated by it, produces death in one of its worst and most painful forms.

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The remedies for these accidents will be found in the vacuum valve, and careful construction in the form and strength of the flues.

4th. *Explosions from defective construction.*

This is, perhaps, one of the most important divisions that can possibly engage our attention, and on which it shall be my duty to enlarge. In a previous inquiry, I have already shown the nature of the strain and the ultimate resistance which the material used in the construction of boilers is able to bear. We have not, however, in all cases, shown the distribution and position in which that material should be placed in order to attain the maximum of strength, and afford to the public greater security in the resisting powers of vessels subject to severe and sometimes ruinous pressure. This is a subject of such importance that I shall be under the necessity of trespassing upon your time, in endeavouring to point out the advantages peculiar to form, and the use of a sound and perfect system of construction.

For a number of years the haycock, hemispherical, and waggon-shaped boilers were those generally in use; and it was not until high pressure steam was first introduced into Cornwall, that the cylindrical form with hemispherical ends, and the furnace under the boiler, came into use. Subsequently this gave way to the introduction of a large internal flue extending the whole length of the boiler, and in this the furnace was placed. For many years this was the best and most economical boiler in Cornwall, and its introduction into this country has effected great improvements in the economy of fuel as well as the strength of the boiler. Several attempts have been made to improve this boiler by cutting away one-half of the end, in order to admit a larger furnace. This was first done by the Butterley Company, and it has since gone by the name of the Butterley boiler. This con-

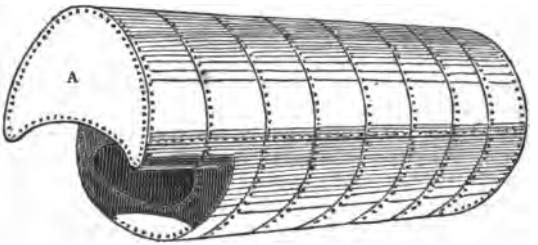

FIG. 1.

struction has the same defects as the haycock or *hemispherical* and waggon-shaped boilers; it is weak over the fire place, and cannot well be strengthened without injury to the part A, Fig. I, of the boiler, from the vast number of stays necessary to suspend the part which forms the canopy of the furnace. Of late years a much greater improvement has, however, been effected by the double flue, B B Fig. 2,

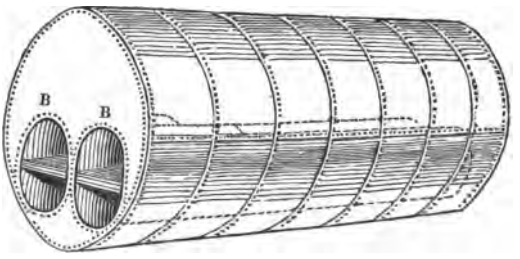

FIG. 2.

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and double furnace boiler, which is now in general use, and has nearly superseded all the other constructions. It consists of the cylindrical form, varying from five to seven feet in diameter, with two flues which extend the whole length of the boiler; they are perfectly cylindrical, and of sufficient magnitude to admit a furnace in each. This boiler is the simplest, and probably the most effective, that has yet been constructed. It presents a large flue surface as the recipient of heat, and the double flues, when riveted to the flat ends, add greatly to the security and strength of those parts. It moreover admits of the new process of alternate firing, so highly conducive to perfect combustion, and the prevention of the nuisance of smoke.

Another boiler, into which a number of small tubes are introduced, exhibits a powerful generator of steam, from the extent of its flue surface, and the facility with which the repairs can be effected. It does not present any greater security against explosion than the boiler with two flues, but its construction on the tubular system effects a great saving in space, and is otherwise productive of all the advantages of economy in the consumption of fuel and the prevention of smoke. This boiler is constructed with a large internal flue, divided in the middle, which admits of two fire-places and alternate firing. In the space which I call the mixing chamber the products of combustion amalgamate, and are thus ignited before they enter the tubes, and from which they issue into the end flues, and from thence to the chimney in the usual way. In this latter construction it will be observed that the boiler is of the same form as the last, and contains the same elements of strength as the double flue boiler, the only difference being a combination of the locomotive and marine tubular system, which contains a large absorbent heating surface in a small space.

It will not be necessary to multiply examples of construction, as I have already described those which I consider best calculated to sustain severe pressure. At the same time, when the parts are judiciously and skilfully arranged, with a grate bar surface well proportioned to the amount of flue surface as the recipient, we may reasonably conclude that we are not far from the maximum of strength, including other important elements in the material, and the consumption of fuel.

The means necessary to be employed for the prevention of accidents in this department of the inquiry, are a knowledge of the principles of construction, and an acquaintance with the strength and properties of the materials used for that purpose.

5th. Explosions arising from mismanagement or ignorance.

To mismanagement, ignorance, and the misapplication of a few leading principles in connection with the use and application of steam, may be traced the great majority of accidents which from time to time occur. Many of these accidents, so fruitful of the destruction of property and human life, might be prevented, if we had well constructed vessels, judiciously united to skill and competency in the management. To convey a few practical instructions to engineers, stokers, and engine-men, would be an undertaking of no great difficulty. A young man of ordinary capacity would learn all that is necessary in a few months; and if placed under competent instructors, he might be made acquainted with the properties of steam,—its elastic force at different degrees of pressure,—the advantages peculiar to sensitive and easy working safety valves,—the necessity for cleanliness and keeping them in good working condition,—the use of water gauges, fusion plugs, indicators, signals, &c., &c., connected with the supply and height of water in the boiler,—the dangers to be apprehended from a scarcity of water,—the danger of explosion when the engine is standing, or

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when the usual channels for relieving the boiler of its surplus steam are stopped. All these are parts of elementary instruction which the stoker, as well as the engineer, should be acquainted with; and no proprietor of a mill, captain of a steam-ship, or superintendent of locomotives, should give employment to any persons unless they can produce certificates of good behaviour, and a knowledge of the elementary principles of their profession.

If these precautions were adopted, greater care observed in the selection of men of skill and responsibility in the construction of boilers, and a more strict and rigid code of laws in the management, we might look forward with greater certainty to a considerable diminution, if not a prevention, of those calamitous events which so frequently plunge whole families into mourning by unexpected and instantaneous death.

As an individual I would cheerfully lend my best assistance to the development of a principle of instruction calculated to relieve the country of the ignorance which pervades that part of the community on which the lives of so many depend. A resolution on the part of those who employ persons of this description, and whose interests are so much at stake, to take only those whose knowledge and character come up to the requisite standard, *and pay for it*, would soon cause, from the economy of the management, and the increased security of their property, a very important change in all the requirements of the economy, as well as the application, of steam. How often do we find implements of danger, and vessels containing the elements of destruction, in the hands of the most ignorant and reckless practitioners, whose insensibility to danger, and total incompetency to judge of its presence, render them above all others the most unfit to be employed. And why? Because they are the very persons, from their defective knowledge, to increase the danger and aggravate the evils they were selected to prevent. It is not the first time that engineers, to secure (if I may use the expression) an insane pressure, have fastened the safety valves, and screwed down the steam valve, closing every outlet, without ever thinking of the fire that was blazing under the boiler. Under such circumstances what could be expected but a blow up? A madman rushing with a lighted match into a powder magazine could not act with greater insanity. Such, however, has been the case, and that arising from want of thought, or what is worse, from the total absence of knowledge which it was the duty of his employer as well as himself to have possessed.

I have on former occasions stated that I am not an advocate for legislative interference either in the construction or management of boilers; but seeing the dangerous tendency of these vessels when placed under the control of ignorance and incapacity, I would forego many considerations to encourage a more judicious and intelligent class of men than has hitherto been employed in the care and management of steam and the steam engine. The reforms necessary to be introduced may be made by the owners of steam engines, steam boats, railways, and others engaged in the use and application of this important element. A desire to enforce more judicious and stringent regulations, to remunerate talent, and to employ only those whose good conduct and superior knowledge entitle them to confidence, is the only sure guarantee of public safety, and the prosperity of the employer.

Lastly, *The remedies applicable for the prevention of accidents arising from explosions.*

Having noticed in the foregoing remarks most of the causes incident to boiler explosions, it now only remains to draw such inferences as will point out the circumstances which it is desirable to cultivate, and others which it is desirable to

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avoid. These circumstances I have endeavoured to class in such a way as to bring the subject prominently forward, and to point out under each head, first, the causes which lead to accident; and secondly, the means necessary to be observed in avoiding it. In a general summary it may not be inexpedient briefly to recapitulate these statements, in order to impress more forcibly upon the mind of those concerned, the necessity for care and consideration in the use of one of the most powerful agents ever placed at our disposal.

One of the most scientific nations of Europe places the greatest confidence, as a means of safety, on the use of a fusible metal plate over the furnace. These plates are alloys of tin and lead, with a small portion of bismuth, in such proportions as will ensure fusion at a temperature something below that of molten lead. In France the greatest importance is attached to these alloys, and in order to ensure certainty as to the definite proportions, the plates are prepared at the royal mint, where they may be purchased duly prepared for use. In this country these alloys are not generally in use, but in this respect I think we are wrong, as boiler explosions are not so frequent in France as in this country, and high pressure steam, from its superior economy, is more extensively used in France than in England. In my own practice I invariably insert a lead rivet, one inch in diameter, immediately over the fire-place, and as lead melts at 640°, I have invariably found these metallic plugs a great security in the event of a scarcity of water in the boiler. I am persuaded many dangerous explosions may be avoided by the use of this simple and effective precaution; and as pure lead melts at 600°, we may infer from this circumstance that notice will be given and relief obtained before the internal pressure of the steam exceeds that of the resisting powers of the heated plates. As this simple precaution is so easily accomplished, I would advise its general adoption. It can do no harm to the boiler, and may be the means of averting explosions and the destruction of many valuable lives.

The fusible metal plates, as used in France, are generally covered by a perforated metallic disc, which protects the alloy of which the plate is composed, and allows it to ooze through as soon as the steam has attained the temperature necessary to insure the fusion of the plate. The nature of the alloy is, however, somewhat curious, as the different equivalents have different degrees of fluidity, and the portion which is the first to melt is found out by the pressure of the steam causing the adhesion of the less fusible parts, but in a most imperfect state, and incapable of resisting the internal force of the steam. The result of these compounds is, the fusion of one portion of the alloy and the fracture of the other, which is generally burst by pressure.

This latter description of fusible plates is different to the lead plug over the fire, which is fused at 600° by the heat of the furnace, and the other, by the temperature of the steam, when raised to the fusible point of the alloy, which varies from 280° to 350°.

Another method is the bursting plate, fixed in a frame and attached to some convenient part of the upper side of the boiler; this plate to be of such thickness and of such ductility as to cause rupture whenever the pressure exceeds that of the weight on the safety valve. There can be no doubt that such an apparatus, if made with a sufficiently large opening, would relieve the boiler; but the objections to this and several other devices are the frequent bursting of those plates, and the effect every change of pressure has upon the material in reducing its powers of resistance, and thus increasing uncertainty as to the amount of pressure in the boiler, as well as the constant renewal of the plates.

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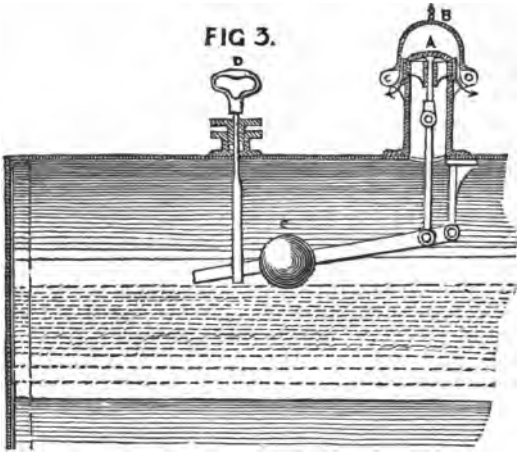
It has already been noticed that one of the most important securities against explosions is a duly proportioned boiler, well constructed; and to this must be added ample means for the escape of the steam on every occasion when the usual channels have been suddenly stopped. The only legitimate outlets under these circumstances appear to me to be the safety valves, which, connected with this inquiry, are indispensable to security. Every boiler should, therefore, have two safety valves, of sufficient capacity to carry off the quantity of steam generated by the boiler. One of these valves should be of the common construction, and the other beyond the reach of the engineer or any other person.

[Fig. 3 is a sketch of a lock-up safety valve, as constructed by Mr. Fairbairn. A is the valve. B is a shell of thin brass, opening on a hinge and secured by a padlock; it is of such a diameter as to allow the waste steam to escape in the direction of the arrows. C is the weight, which may be fixed at any part of the

FIG 3.



lever, to give the desired amount of pressure, but which cannot be fixed or altered unless the boiler is opened to allow a man to get inside. D is a handle, having a long slot, by which the valve may be relieved or tried at any time, to obviate the liability of its corroding or being jammed; the engineer cannot, however, put any additional weight upon the valve by this handle.]

Whilst tracing the causes of explosions from a deficiency of water in the boiler, I have recommended as the usual precautions, good pumps, self-acting feeders, water cocks, glass gauges, floats, alarms, and other indicators which mark the changes and variation in the height of the water. To these may be added the steam whistle, but, above all, the constant inspection of a careful, sober, and judicious engineer. Above all other means, however ingeniously devised, this is the most essential to security, for on that official depends, not only the security of the property under his charge, but also the interests of his family, and the lives of all those within the immediate influence of his operations. One of the most important considerations in this and every other department of management is cleanliness and the careful attention of a good engineer.

Explosions produced from collapse have their origin in different causes to those arising from a deficiency of water, and the only remedy that can be applied is the vacuum valve and the cylindrical or spheroidal form of boiler.

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Defective construction is unquestionably one of the greatest sources of the frightful accidents which we are so frequently called upon to witness. No man should be allowed unlimited exercise of judgment on a question of such vital importance as the construction of a boiler, unless duly qualified by matured experience in the theoretical and practical knowledge of form, strength of materials, and other requirements requisite to insure the maximum of sound construction. It appears to me equally important that we should have the same proofs and acknowledged system of operations in the construction of boilers, as we have in the strength and proportions of ordnance. In both cases we have to deal with a powerful and dangerous element; and I have yet to learn why the same security should not be given to the general public as we find so liberally extended to an important branch of the public service. In the ordnance department at Woolwich (with which I have been more or less connected for some years) the utmost care and precision is observed in the manufacture of guns; and the proofs are so carefully made under the superintendence of competent officers, as to render every gun perfectly safe to the extent of 1,000 to 1,200 rounds of shot.

Boilers and artillery are equally exposed to fracture, and it appears to me of little moment whether the one is burst by the discharge of gunpowder, or the other by the elastic force of steam.

Taking into consideration all the circumstances connected with the bursting of boilers and the bursting of guns, and looking at the active competition which exists, and is likely to be extended, in manufactories, railway traffic, and steam navigation, rendering it every day more desirable to reduce the cost by an extended use of steam at a much higher pressure, it surely becomes a desideratum to secure the public safety by the introduction of some generally acknowledged system of construction that will bear the test of experience, and involve a maximum power of resistance. The most elaborate disquisitions have taken place, by the most distinguished men of all ages, since the invention of gunpowder, to discover the strength and form of guns of every description. Surely boilers are equally if not more important, as the sacrifice of human life appears to me much greater in the one case than the other. It is, therefore, a subject of paramount importance to the public to know that the facts of scientific inquiry, and the knowledge of practical skill, have combined to give *undeniable security as well as confidence*, that boilers are properly constructed, and capable of bearing at least *six times* their working pressure.

On the question of explosions arising from mismanagement and ignorance, we have little further to add; and it now only remains to state, that the subject of security from boiler explosions is of such importance as to call for more able exponents than myself. I have endeavoured to trace the causes of these lamentable occurrences, and to draw such deductions therefrom as I trust may be useful in at least mitigating, if not almost entirely averting, the danger.

I repeat the means of prevention and the precautions necessary to be observed in the construction and management of boilers.

1st. To avoid explosions from internal pressure, cylindrical boilers of maximum form and strength must be used, including all the necessary appendages of safety valves, &c.

2nd. Explosions arising from deficiency of water may be prevented by the fusible alloys, bursting plates, good feed pumps, water gauges, alarms, and other marks of indication; but above all, the experienced eye and careful attention of the engineer is the greatest security.

3rd. Explosions from collapse are generally produced from imperfect construc-

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tion, which can only be remedied by adopting the cylindrical form of boiler, and a valve to prevent the formation of vacuum in the boiler.

4th. Explosions from defective construction admit of only one simple remedy, and that is, the adoption of those forms which embody the maximum powers of resistance to internal pressure, and such as we have already recommended for general use.

Lastly. Good and efficient management, a respectable and considerate engineer, and the introduction of such improvements, precautions, and securities as we have been able to recommend, will not only ensure confidence, but create a better system of management in all the requirements necessary to be observed for the prevention of steam boiler explosions.

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ON THE CONSUMPTION OF FUEL

AND THE

PREVENTION OF SMOKE.

There is, perhaps, no subject so difficult, and none so full of perplexities, as that of the management of a furnace and the prevention of smoke. I have approached this inquiry with considerable diffidence, and after repeated attempts at definite conclusions, have more than once been forced to abandon the investigation as inconclusive and unsatisfactory. These views do not arise from any defect in our acquaintance with the laws which govern perfect combustion, the economy of fuel, and the consumption of smoke. They chiefly arise from the constant change of temperature, the variable nature of the volatile products, the want of system, and the irregularity which attends the management of the furnace. Habits of economy and attention to a few simple and effective rules are either entirely neglected, or not enforced. It must appear obvious to every observer, that much has yet to be done, and much may be accomplished, provided the necessary precautions are taken, first to establish, and next to carry out, a comprehensive and well-organized system of operations. If this were accomplished, and the management of the furnace consigned to men of intelligence properly trained to their respective duties, all these difficulties would vanish, and the public might not only look forward with confidence to a clear atmosphere in the manufacturing towns, but the proprietors of steam engines would be more than compensated by the saving of fuel, which an improved system of management and a sounder principle of operation would ensure. Under the hope of the attainment of these objects, I shall endeavour to show, from a series of accurately conducted experiments, that the prevention of smoke, and the perfect combustion of fuel, are synonymous, and completely within the reach of all those who choose to adopt measures calculated for the suppression of the one, and the improvement of the other.

On a former occasion I had the honour of presenting to the British Association an inquiry into the merits of Mr. C. W. Williams's Argand furnace, compared with those of the usual construction. On that occasion it was found, from an average of a series of experiments, that the saving of fuel (inclusive of the absence of smoke) was in the ratio of 292 to 300, or as 1 : 1.039; being at the rate of 4 per cent. in favour of Mr. Williams's plan. Since then a considerable number of experiments have been made by Mr. Houldsworth, Mr. Williams, and others; and having occasion in the course of this inquiry to refer to these researches, it will be unnecessary for the present to notice them further than to observe, that they have been made with great care, and present some curious and interesting phenomena in the further development of this subject.

The complex nature of the investigation has rendered it necessary to divide the subject into sections, for the purpose of observing, not only the relative tendencies and connexion of each, but to determine, by a series of comparative

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results, the law on which perfect combustion is founded, and its practical application ensured.

Keeping these objects in view, the heads of inquiry will be :—

I. The Analysis or Constituents of Coal and other Fuels.

II. The relative Proportions of the Furnace, and Forms of Boilers.

III. The Temperature of the Furnace and surrounding Flues.

IV. The Economy of Fuel, Concentration of Heat, and Prevention of smoke.

Lastly. General summary of results.

1. *The Constituents of Coal and other Fuels.*

The first practical inquiries into the nature and constituents of coal, are probably those of Dr. Thomson and Mr. Mushet; several others have investigated their chemical composition, but the discrepancies which exist in the varied forms of analysis render them of little value when applied to the useful arts. Dr. Thomson examined four distinct species of coal, of which the following are the results :—

Quality	Specific gravity.	Carbon.	Hydrogen.	Azote.	Oxygen.
Caking coal	1.269	75.28	4.18	15.96	4.58
Splint coal	1.290	75.00	6.25	6.25	12.50
Cherry coal	1.263	74.45	12.40	10.22	2.93
Cannel coal	1 272	64.72	21.56	13.72	...

Dr. Ure also supplies an analysis of splint and cannel coal, which differ from those experimented upon by Dr. Thomson, as follows :—

Quality.	Specific gravity.	Carbon.	Hydrogen.	Azote.	Oxygen.
Splint coal	1 266	70.90	4.30	...	24.80
Cannel coal	1.228	72.22	3.93	2.8	21.05

The chief difference between the experiments seems to consist in the increased quantity of hydrogen in Dr. Thomson's cannel coal, and the total absence of oxygen, which in Dr. Ures specimens were found in excess.

The next authority is Mr. Mushet, who analysed nearly the whole of the Welsh coals, and some others, of which the following are selected, viz.—

Quality.	Specific gravity.	Carbon.	Ashes.	Volatile matter.
Welsh furnace coal	1.337	88.068	3.432	8.800
Welsh stone coal	1.393	89.700	2.300	8.000
Welsh slaty coal	1.409	82.175	6.725	9.100
Derbyshire furnace coal ...	1.264	52.882	4.288	42.830
Derbyshire cannel coal ...	1.278	48.362	4.638	47.000

Again, we have some of the American anthracites, with upwards of 90 per cent. of carbon and 3.6 of volatile matter, which correspond with nearly all the other descriptions of anthracites as given by Mr. Mushet, and more recently by Dr. Kane, in his excellent work " On the Industrial Resources of Ireland."

In addition to the above, Dr. Fife has given some valuable experiments on coal, wherein he does not materially differ in the bituminous qualities from those

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of Mr. Mushet. The results of Dr. Fife's experiments were found to be in the bituminous and anthracite kinds :—

	Bituminous.	Anthracite.
Moisture	7.5	4.5
Volatile matter	34.5	13.3
Fixed carbon	50.5	71.4
Ashes	7.5	10.8
	100.0	100.0

It will be observed from these experiments that considerable differences exist as to the quantity of carbon contained in each sort; and provided it be correct that the heating power of any description of fuel be a proportional of the quantity of carbon it contains, it then follows that the anthracite must be greatly superior to the bituminous qualities, which yield little more than one-half the quantity. Considerable difficulty is, however, encountered in the combustion of the anthracite coal, as intense heat is not only an element, but time, and a large quantity of oxygen, are absolutely necessary to volatilize its products. It has been known to pass twice through an iron smelting furnace, and be subjected for upwards of forty hours to the temperature of melting iron, without being affected beyond the exterior surface, having been calcined to a depth of not more than three-fourths of an inch. Such, however, is the obduracy of its character, that intense heat makes little or no impression upon it. To burn anthracite coal effectually, and to extract the whole of its volatile products, it must be broken into small pieces, and thrown upon a furnace having a large supply of oxygen passing continually through it.

In the combustion of bituminous coal the operation is totally different, being partly friable, and splitting into fragments as the gases are evolved; hence arises the superior value of that description of fuel in almost every branch of the industrial arts.

The Newcastle, and the best qualities of the Durham coal, are exceptions to most others of the bituminous kind; they contain a much greater quantity of carbon, and are thus better fitted for the furnace. From some accurate experiments by Mr. Richardson they are found to contain :—

Carbon	85.613	
Hydrogen	5.205	Specific gravity
Azote and oxygen	7.226	1.278.
Ashes	1.956	
	100.	

The Lancashire coals approach nearer to the Newcastle and Durham than most others; and, taking the mean of some recent experiments, they contain :—

Carbon	82.95
Hydrogen	5.86
Azote and oxygen	7.93
Ashes	3.26
	100.

The specific gravity of the Lancashire coal is rather more than that of the Newcastle coal, but in other respects their constituents are much alike, with the exception of a greater proportion of ashes in the former than is found in the finer qualities of the latter.

Dr. Kane, in his recent work "On the Industrial Resources of Ireland," (already alluded to), has given some valuable information on the properties of

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the Irish anthracites and other coals found in different districts of the country. He also ascertained the value of the different beds of lignite which retained their original structure of wood, which burned with a brilliant light, and left a black dense charcoal.

The constituents of two specimens analysed by Dr. Kane, gave :—

	1.	2.
Volatile matter	57.70	53.70
Pure charcoal	33.66	30 09
Ashes	8.64	16.21
	100.	100.

From the above it would appear that the economic value of lignite is about two-thirds of an average quality of good coal; and comparing these with other results obtained from similar lignites, two-thirds may fairly be taken as the calorific value of this description of fuel. Dr. Kane further examined a great variety of turf, and amongst others those prepared by Mr. C. W. Williams from the bogs of Cappage, Kilbeggan, Kilbaken, &c.; the elementary products of which are, according to Dr. Kane, as follows :—

	Cappage.	Kilbeggan.	Kilbaken.
Carbon	51.05	61.04	51.13
Hydrogen	6.85	6.67	6.33
Oxygen	39.55	30.46	34.48
Ashes	2.55	1.83	8.06
	100.	100.	100.

It will be unnecessary to exemplify a greater variety of fuels, such as the different kinds of wood used in America, Russia, and different parts of the continent. In this country timber is seldom, if ever, used; and taking the comparative merits of the fuels already enumerated, it will be found (in assuming the quality of carbon contained in each as the measure of their respective values) that the Welsh furnace coal and the Newcastle and Lancashire coals stand pre-eminent in the order of their heating powers, either as regards their application to the furnace, or to the ordinary purposes of domestic life.

The American anthracites, which in some cases contain upwards of 90 per cent. of carbon, are extensively used in that country; and, assuming the mean, 91.4, of Professor Johnston's experiments to be correct, and calling it at 1,000, we then have an approximate value of the different fuels experimented upon and in general use in this country.

TABLE OF COMPARATIVE RESULTS, showing the calorific and economic Value of different kinds of Fuel.

No.	Quality.	Specific gravity.	Value.
	American anthracite coal	...	1000
1	Welsh anthracite coal	1.393	981
2	Welsh furnace coal	1.337	963
3	Newcastle coal	1 278	936
4	Lancashire coal	1.293	900
5	Welsh slaty coal	1.409	898
6	Scotch caking coal	1.263	822
7	Scotch cherry coal	1.263	813
8	Scotch splint, 75.00 / Scotch splint, 70.90 — Mean, 72.95	1.278	799
9	Scotch cannel, 64.72 / Scotch cannel, 72 22 — Mean, 68.47	1.250	749
10	Derbyshire furnace coal	1.264	578

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In this table the economic value is assumed to be a proportional of the quantity of carbon contained respectively in each sort of coal; and, provided the lignites and turfs are excepted, the others may safely be taken as nearly the correct value of the principal mineral fuels of the kingdom.

II. *The relative Proportions of the Furnace and the Forms of Boilers.*

On this part of the subject there are several points worthy of attention, namely, the proportions of the furnaces of stationary boilers of different constructions; the dimensions and position of those with exterior and interior fires; and the principle of form which approaches the nearest to a maximum calorific effect.

It is obvious that the hemispherical and waggon-shaped boilers are the best calculated to ensure abundance of space; and the furnace being detached and entirely clear of the boilers, a discretionary power is thus vested in every person choosing to experiment as to the length, breadth, or height of the hearth plate and bars which contain the fuel. Hence arise the anomalies which exist, and the innumerable theories which are advocated in every direction for improved furnaces and perfect combustion.

These discrepancies create great perplexities; and as much depends upon the management of the fire, and the will as well as skill of the engineer, it is next to impossible, from such a mass of conflicting evidence, to deduce anything like a correct proportional of the area of the grate-bar and the recipient surface.

From a careful examination of some of the best constructed boilers and furnaces in Manchester, the following results were obtained:—

No. of Boilers.	Area of grate-bars in feet.	Recipient internal surface in feet.	Recipient external surface in feet.	Total heated surface in feet.	Ratio of grate-bars to heating surface.	Remarks.
6	36.0	195 0	.....	.....	.....	In the first six boilers the external flues could not be measured.
1	30.5	167.2	175.0	342.2	1 : 11.2	
2	36.5	201.0	267.5	468.5	1 : 12 7	
2	28.3	154.8	186 5	353.3	1 : 12 0	
2	28.7	137.3	167.0	304.3	1 : 10.8	
2	40.6	150.4	207.3	357.7	1 : 8.9	
Mean	33.4	162.1	199.4	365.2	1 : 11.1	

The ratio of grate-bar to absorbing surface is, therefore, as 1 : 11.1, which, taken from fifteen different boilers of the best construction, and worked with considerable skill, gives a fair average of the proportions of the furnace and flue surface of each. Now, on comparing the above with the boilers at work in Cornwall, it will be found that their relative proportions are as 1 to 25; the Cornish boilers presenting from two and a half, and in some instances three times, the surface exposed to the action of the fire, in the ratio of the furnace to the flue as a recipient of heat. Taking the disparities as thus exhibited, it must appear evident that exceedingly defective proportions must somewhere exist, otherwise the anomalous comparison of a small fire and a large absorbent surface could not be maintained, unless the former practice of large fires and limited flue surface had been found injurious and expensive. That a great waste of valuable fuel is the consequence of these defective proportions, is abundantly manifest from the results obtained in the quantity of water evaporated by a pound

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of coals in each. For example, 1 lb. of good coal will evaporate in the Cornish boiler about 11½ lbs of water; and the utmost that the best waggon-shaped boiler has been known to accomplish is 8.7 lbs. of water to the pound of coal. Hence the advantage of a small furnace and large flue surface, united, however, to abundance of boiler space, in order to attain a maximum effect by a slow and progressive rate of combustion. From the facts thus recorded, and the returns regularly made of the performances of the Cornish engines and boilers, it will no longer admit of doubt as to the superiority of the practice which exists in one country as compared with that in the other. Persons unacquainted with the subject have attributed the saving to the engine; but that doctrine, although in some degree correct, is no longer tenable, as experiments and the monthly returns unite in proving that part of the economy is due to the boiler; and the proportion of flue surface on the Cornish construction being so much greater, we reasonably infer that the recipient surface of the hemispherical and waggon boilers is insufficient for the amount of fire-bar surface acting upon it.

These observations have in a great measure been corroborated by the introduction into the Lancashire districts of the cylindrical form, with a large circular flue, extending the whole length of the boiler. In this flue the furnace is placed, and being confined within certain limits it no longer admits of disproportionate enlargement, but, from the very nature of its construction, forces old plans and old prejudices to yield to positive improvement.

The effect of the change is a progressive and improved economy in the consumption of coal, with a larger extent of flue surface, and, what is probably of equal value, a stronger and much more perfect boiler.

Irrespective of the changes of form and management of boilers which are in progress, it may be proper to notice a still further improvement in construction which has recently taken place, and where a still greater economy is effected. This is a mean between the Cornish single flue boiler and the tubular boiler; it is perfectly cylindrical, and contains two circular flues, varying from 2 feet 6 inches to 2 feet 9 inches diameter, extending throughout its whole length, as represented and explained in another place in drawings which are annexed. Towards the front end the flues are made slightly elliptical, in order to receive the furnace grate-bars, hearth-plates, &c., to give sufficient space over the fire, and to admit a free current of air under the ash-pit. On this plan it will be observed that each furnace is surrounded by water in every direction, with large intermediate spaces to allow a free circulation of the water, as the globules of heat rise from the radient surface over the fires and the other intensely heated parts of the flues. Another advantage is the position of the receptacle for the sedimentary deposits, which do not take place over the furnace, as in the old construction, but in the lower region of the boiler, where the temperature is lowest; thus affording greater security from incrustation and other causes of an injurious tendency.

On the evaporative powers of boilers, it has already been shown that the process, to be conducted with economy, depends upon one of two causes, or both; first, on the due and perfect proportions of the furnace; secondly, which is more probable, on the quantity of flue surface exposed to the action of heat. No doubt they are both important agents in the procuration and generating of steam, but the recipient surface is so important, that the measure of all boilers, as to their economy and efficiency, in a great degree depends upon the enlargement of those important parts. Taking, therefore, the amount of the flue surface in a boiler exposed to the passing currents of heat as a criterion of its economic value,

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we shall then have, according to computation, a summary of comparison as follows:—

No.	Description of Boiler.	Cubic contents in feet.	Area of heated surface in feet.	Ratio of the area of heating surface to cubic contents.
1	Old hemispherical boiler	420	128	1 : 3 28
2	Common waggon boiler, without middle flue ...	1044	320	1 : 3 26
3	Waggon boiler, with middle flue	894	432	1 : 2 06
4	Cylindrical boiler, without middle flue.....	789	225	1 : 3 50
5	Cylindrical boiler, with middle flue	579	360	1 : 1 65
6	Cylindrical boiler, with eight ten-inch iron tubes	605	567	1 : 1 06
7	Improved boiler, with two middle flues.....	573	548	1 : 1.01

On a comparison of the above table, it will be seen that the generative powers of a boiler do not depend upon its cubic contents, nor yet upon the quantity of water it contains, but upon the area of flue surface exposed to the action of heat; and that the nearer the area of the flue surface approaches the cubic contents, the greater the economy and more perfect the boiler.

This has been proved by experiment, and also by practice in the use of Nos. 6 and 7 boilers, where the generative powers have been much increased, and where they approach nearer to the maximum than any other, excepting, probably, those with a number of small tubes, such as the locomotive, and the present construction of marine boilers. These latter are, however, not so well adapted for stationary purposes, nor yet are they calculated for the attainment of other objects contemplated in this report.

It has already been stated that the relative areas of fire-grate and flue surface, taken from a series of observations, are as 1 to 11,* and in the average of Cornish boilers as 1 to 25. Now, if we take the mean of these two, and fix the ratio at 1 to 18, we shall have a near approximation to a maximum effect; and, for general practice, it will be found that such a proportion will better serve the interests of the public, and of parties employing steam boilers, than the extreme of 1 to 25 or 1 to 30, where a great increase of boiler power must be the result. In many situations, such as the large manufacturing towns, this cannot be accomplished, and to enforce such a regulation by legislative or municipal enactments, would be, to say the least, inexpedient and oppressive. Taking, therefore, the experiments, observations, and other circumstances bearing upon these points, into consideration, it will appear that the circular boiler, with an enlarged and extended flue surface, and accurately proportioned furnaces of about 1 to 18, is the best calculated under all circumstances for the economy of fuel, and those objects which have yet to be considered.

III. *The Temperature of the Furnace and the surrounding Flues.*

It is a difficulty of no ordinary description to ascertain with sufficient accuracy the temperature of a furnace. In fact, every fire and every furnace is continually changing its temperature, as well as the nature of the volatile products, as they pass off during the process of combustion. When a furnace is charged with a fresh supply of fuel, its temperature is lowered, and that from two causes: first, by the absorption of heat which the cold fuel takes up when thrown upon the fire; and, secondly, by a rush of cold air through the open door of the furnace. Attempts have been made to remedy these evils by the aid of machinery and

* Since the above was written, I have received from my friend, Mr. Andrew Murray, of the Royal Dockyard, woolwich, a series of experimental researches, some of which will be found at the close of the report.

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continuous firing; but taking the whole of the existing schemes into account, and bestowing upon them the most favourable consideration, it is questionable whether they are at all equal (either as regards efficiency or economy) to the usual way of working the fires by hand. I am persuaded the latter plan is the best; and, provided a class of careful men were trained to certain fixed and determined regulations, and paid, not in the ratio of the quantity of coals shovelled on the fire, but in proportion to the saving effected, we should not then have occasion for the aid of machinery as an apology for ignorance.

Operations of this kind require but a small portion of physical strength in supplying a furnace with fuel, (which a machine can do), but some measure of intelligence is necessary to watch over and assist nature in the development of those laws which regulate as well as govern the process of combustion.

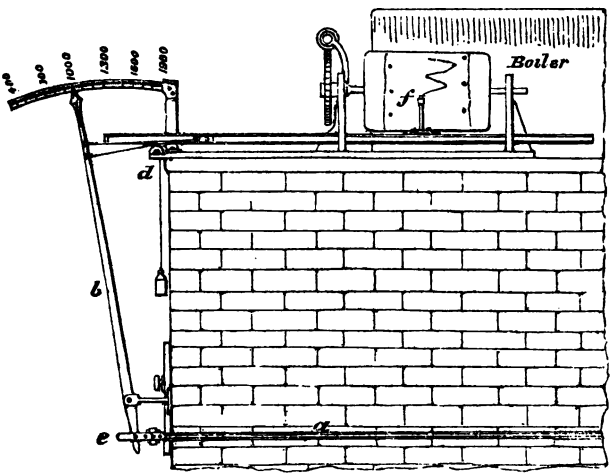
Viewing the subject in this light, it will not be uninteresting if we attempt to exhibit some of the important and exceedingly curious changes which take place in the ordinary process of heating a steam-engine boiler.

For these experiments we are indebted to Mr. Henry Houldsworth, of Manchester; and, having been present at several of the experiments, I can vouch for the accuracy with which they were conducted, and for the very satisfactory and important results deduced therefrom.

In giving an account of Mr. Houldsworth's experiments, it will be necessary to describe the instrument by which they were made, and also to show the methods adopted for indicating the temperature, and the changes which take place in the surrounding flues.

The apparatus consists of a simple pyrometer, with a small bar of copper or iron (*a* in the following sketch) fixed at the extreme end of the boiler, and projecting through the brick-work in front, where it is jointed to the arm of an index lever *b*, to which it gives motion when it expands or contracts by the heat of the flue.

PYROMETER.



The instrument being thus prepared, and the bar supported by iron pegs driven into the side walls of the flue, the lever (which is kept tight upon the bar at the

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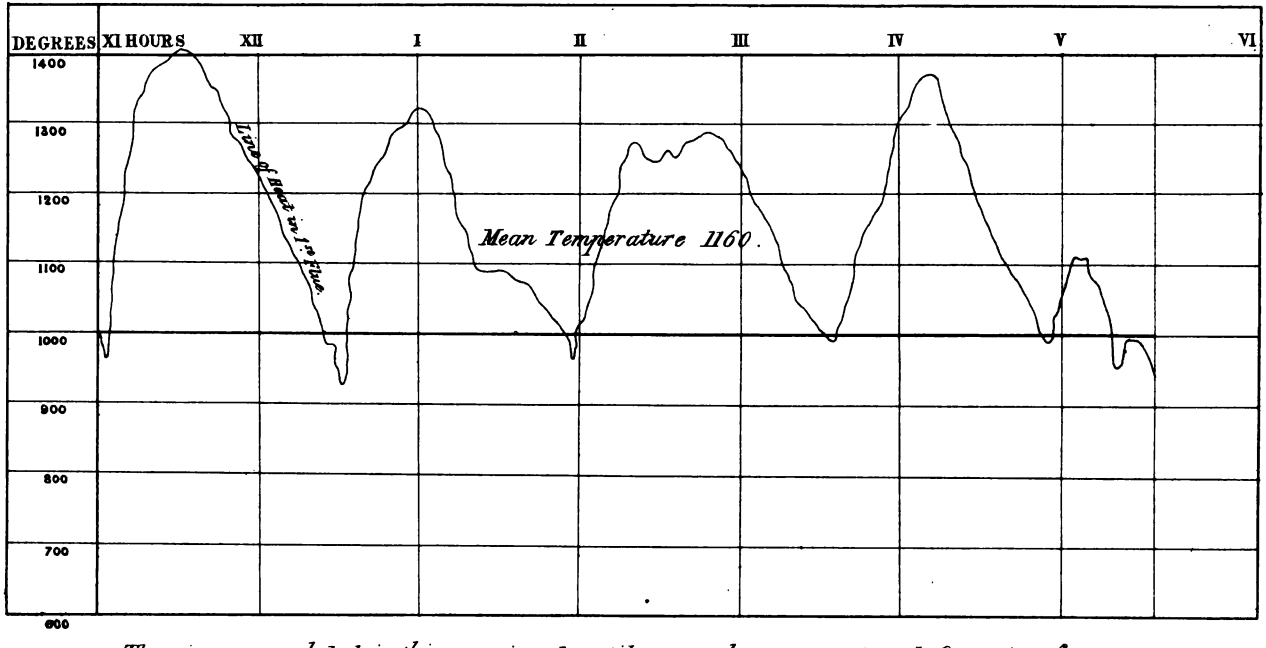
DIACRAM 2.



The air was regulated in this experiment until no smoke was produced. Quantity of water evaporated 1560 Gallons – 7.7 lbs of water to 1 lb of coal.

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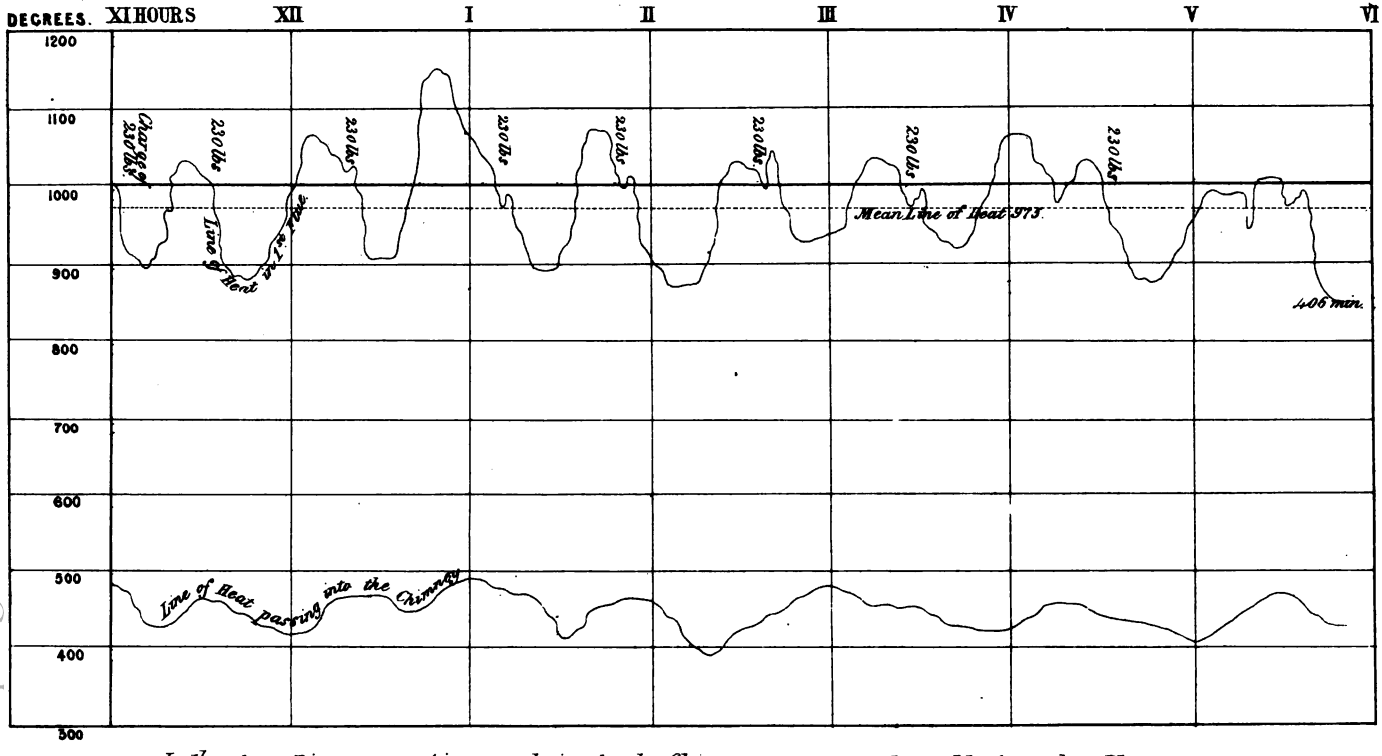
DIAGRAM I.



In the above Diagram no Air was admitted, the Chimney emitting a dense black smoke. Water evaporated. 930 Gallons = 5·05 of water to 1 lb of coal.

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point *e* by means of a small weight over the pulley at *d*) is attached, and motion ensues. The long arm of the lever at *d* gives motion to the sliding rod and pencil *f*, and by thus pressing on the periphery of a slowly revolving cylinder, a line is inscribed corresponding with the measurements of the long arm of the lever, and indicating the variable degrees of temperature by the expansion and contraction of the bar. Upon the cylinder is fixed a sheet of paper, on which a daily record of the temperature becomes inscribed, and on which are exhibited the change as well as the intensity of heat in the flues at every moment of time. In using this instrument it has been usual to fix it at the medium temperature of 1000°, which, it will be observed, is an assumed degree of the intensity of heat, but a sufficiently near approximation to the actual temperature for the purpose of ascertaining the variations which take place in all the different stages of combustion consequent upon the acts of charging, stirring, and raking the fires. These are exemplified by the annexed diagrams, No. I. and No. II.

On a careful examination of the diagrams, it will be found that the first was traced without any admixture of air, except that taken through the grate-bars; the other was inscribed with an opening for the admission of air through a diffusing plate behind the bridge, as recommended by Mr. C. W. Williams. The latter, No. II., presents very different figures: the maximum and minimum points of temperature being much wider apart in the one than the other, as also in the fluctuations which indicate a much higher temperature, reaching as high as 1,400°, and seldom descending lower than 1,000°, giving the mean of 1,160°.

Now, on comparing No. II. with No. I., where no air is admitted, it will be found that the whole of the tracings exhibit a descending temperature, seldom rising above 1,100° and often descending below 900°, the mean of which is 975°. This depression indicates a defective state in the process, and although a greater quantity of coal was consumed, (2,000 lbs. in 396 minutes in the No. II. experiment, and 1,840 lbs. in 406 minutes in No. I.,) yet the disparity is too great when the difference of temperature and loss of heat are taken into consideration. As a further proof of the imperfections of No. I. diagram, it is only necessary to compare the quantities of water evaporated in each in order to ascertain the difference, where in No. I. experiment 5.05 lbs. of water are evaporated to the pound of coal, and in No. II. one-half more, or 7.7 lbs. is the result.

Taking the results thus indicated, it will appear evident that the admission of a certain quantity of atmospheric air behind the bridge operates most advantageously, inasmuch as it combines with its constituents in due proportions, and by these means the gases are inflamed under circumstances favourable to the extraction of heat and consumption of smoke. The whole process is, therefore, distinguishable by the fact of one diagram presenting a decreasing temperature when air is not admitted, and the other an increasing column when it is introduced. If no air is admitted, except through the grate-bars, and there happens to be a compact charge in the furnace, the consequence is that the gases pass through the flues unconsumed, and accompanied with a dark volume of smoke, which is invariably present on such occasions.

It will not be necessary in this instance further to increase the number of diagrams, as No. I., which exhibits the variations and results of the intensity of heat when air is not admitted, and No. II., (with an aperture of forty-five square inches constantly open), will be found encouraging features for its admission in duly regulated proportions. These two diagrams will, therefore, sufficiently explain the varied changes of temperature which exist, and as all the other thirty are (with occasional deviations) nearly alike, the following table of

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results will probably answer the same purpose as if the whole were given in detail :—

TABLE OF RESULTS, selected from thirty experiments obtained by Mr. Houldsworth's Pyrometer, indicating the mean temperature of the flues in a steam-engine boiler, and the effects produced by the admission of air through regulated and permanent apparatus behind the bridge :—

No. of Experiments as marked on the diagrams	Description of coal used.	Aperture for the admission of air in square inches.	Coals burnt per hour.	Water evaporated by 1 lb. of coal in lbs.	Mean temperature in the front flue.	Relative value in the ratio of water evaporated.
12 13 and 28	Clifton } mean Oldham }	No air	243.00	6.21	977°	100 : 000
9, 10, 11.	Clifton	.....	278.40	5.41	973°	100 : 87.1
7 and 8	Clifton	45	280.8	6.85	1.165°	100 : 110.3
15 to 22	Clifton	{ Regulated by hand }	265.8	6.94	1.122°	100 : 110.7
14	Clifton	45	279 0	6.60	1.220°	100 : 106.2
30	Clifton	Regulated	279.0	6 80	1.160°	100 : 109 5
24	Oldham	35	243 0	6.85	1.080°	100 : 110.3
26	Oldham	24	229.2	7.40	1.050°	100 : 119.1
23	Oldham	Regulated	230.4	7.70	1.070°	100 : 124.0
25 to 29	Oldham	Regulated	216.6	8.30	1.053°	100 : 133.6
27	{ Mixed, half of each sort. }	... ..	243.0	7 20	1.060°	100 : 115.7

By comparing the results as given above, it will be found that in taking the quantity of water evaporated by 1 lb. of coal as the measure of economic value, the mean of nearly the whole experiments (excepting only Nos. 12, 13, and 28, where air is not admitted) is as 100 to 112.65, or about 12¼ per cent. in favour of a regulated and continuous supply of air. Taking, however, the mean of experiments, 25 to 29, and comparing it with some of the others, it will be observed that a much higher duty is obtained; and having accomplished a maximum, there appears no reason for doubting why it should not be continued, and still further advantages secured by a judicious arrangement of the furnace for the admission of oxygen to the uninflamed gases, which under other circumstances would make their escape into the atmosphere unconsumed. In furnishing this supply it is not absolutely necessary to administer it immediately behind the bridge, as the same quantity of air taken through the grate-bars, or in at the furnace-doors, would nearly effect the same purpose, not only as regards the quantity of heat evolved, but also as respects the transparency of the gases and the consequent disappearance of smoke.

Mr. Houldsworth estimates the advantages gained by the admission of air (when properly regulated) at 35 per cent., and when passed through a fixed aperture of 43 square inches, at 34 per cent. This is a near approximation to the mean of five experiments, which, according to the preceding table, gives 33½ per cent., which probably approaches as near the maximum as can be expected under all the changes and vicissitudes which take place in general practice.

On a cursory view of the subject, it is obvious that the quantity of air necessary to be admitted will greatly depend upon the nature and quality of the fuel used. In a light burning fuel, such as splint and cannel coal, less air will be required, as the charge burns freely with clear spaces between the grate-bars, and is attended by less risk of cementation than the caking coal, which in some cases completely seals the openings, and thus deprives the fuel of that quantity of air necessary for its combustion. Under such circumstances a permanent opening will be found exceedingly efficacious, and that more particularly when the heat

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vitrifies the earthy particles of the coal, and forms clinkers on the top of the grate-bars. In the use of this description of fuel the permanent apertures are of great value.

IV. *The Economy of Fuel, Concentration of Heat, and Prevention of Smoke.*

Irrespective of the intensity of heat, form of boilers, and quality of fuel, there are other conditions connected with the phenomena of combustion which require attentive consideration before that process can be called perfect, or before economy or the prevention of smoke can be attained. It is perfectly clear, that although we may possess abundance of excellent fuel, and a perfect knowledge of all the elements necessary for its combustion, yet we are still far short of attaining our object, unless a regard to economy is strictly kept in view. A manufacturer may have well-proportioned boilers, excellent furnaces, and good fuel, but with all these advantages he will not succeed, unless the whole of the elements at his command are properly and economically combined, and that upon fixed laws already determined for his guidance. Count Rumford, in his admirable Essays on the Economy of Heat, truly observes, that "No subject of philosophical inquiry within the limits of human investigation is more calculated to excite admiration and to awaken curiosity than fire, and there is certainly none more extensively useful to mankind. It is owing, no doubt, to our being acquainted with it from our infancy that we are not more struck with its appearance, and more sensible of the benefits we derive from it. Almost every comfort and convenience which man by his ingenuity procures for himself is obtained by its assistance, and he is not more distinguished from the brute creation by the use of speech, than by his power over that wonderful agent."

Such was the opinion of one of the most eminent philosophers of his time, and such were the pertinency of his remarks and the depth of his researches, that had he lived in the present instead of the close of the last century, he would not only have extended and enlarged our views on the management and economy of heat, but he would have expressed astonishment at the increase, the immense extent of expenditure, and the lavish and culpable waste of fuel by which we are surrounded on every side. It is true we have some exceptions, such as those in Cornwall and some parts of the continent, where fuel is expensive; but taking the aggregate, it might be said, without fear of contradiction, that if one-half of the fuel now used were properly applied, it would perform the same service, and afford the same comforts, as we now derive from the whole of our mineral products. This is a great reflection upon the philosophy as well as the economy of the age, and I think it can be shown that one-half the fuel now wasted might be saved with great advantage to individuals, and with increased benefit as well as comfort to the public. The wasteful expenditure which exists does not arise so much from ignorance as from prejudice, and a close adherence to old and imperfect customs. We all, more or less, venerate the works of antiquity, but unfortunately we forget to draw the distinction between what is really ancient and sound in principle, and what is imperfect in practice. Hence follows a blind adherence to established usage, and the consequent propagation of all the defects as well as the perfections of the system. Now this state of things should not exist, as we have the experiments of Watt, Rumford, Davy, Parkes, and many others before us; and adding to these the excellent treatise of Mr. C. W. Williams on the combustion of coal and prevention of smoke, we are enabled by these means to establish a sound and much more perfect as well as economical system of combustion. Keeping these objects in view, we shall endeavour to determine some fixed principle on which may be founded the prevention of smoke, concentration of heat, and economy of fuel.

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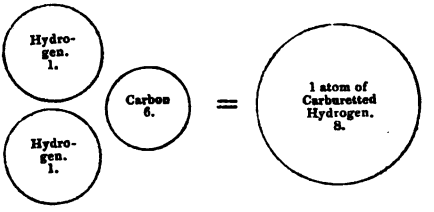
It is well known that in practical operations there is no combustion without oxygen as its supporter; and as that important element cannot be procured for general purposes without the other constituents of atmospheric air, it follows, that in order to effect combustion, a regular supply of this compound must be constantly at command. Now it is not the facility, but the control and regulation, of the supply of air which requires attention, and on this point of the inquiry we must refer to the researches of Mr. C. W. Williams, where, in speaking of "gaseous combinations," he shows that much depends upon the conditions and proportions in which the gases evolved during the process of combustion combine with the oxygen of the air. And in order to effect this, it is necessary for those entrusted with the management of furnaces to know the "equivalents" or definite proportions under which these combinations take place. On this head it will be sufficient to observe, that the principal gases evolved from coal in a state of combustion are carburetted hydrogen, bicarburetted hydrogen, and some others, such as carbonic acid gas, carbonic oxide, &c., the properties of which it is not requisite on this occasion to investigate, but to confine the inquiry to the union of carburetted hydrogen, bicarburetted hydrogen, and atmospheric air. Following, therefore, the Daltonian theory, it will be found that the constituents of one atom of carburetted hydrogen consist of the following symbols, each representing an atom, and the figures the weight:—

Carburetted hydrogen.

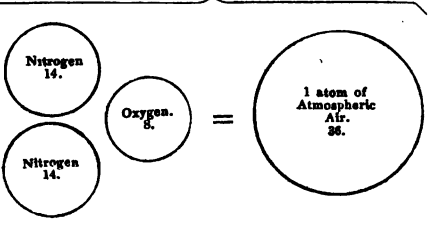


Carburetted hydrogen is, therefore, composed of 2 hydrogen and 1 carbon = 1 carburetted hydrogen. In weight 2 hydrogen + 6 carbon = 8 carburetted hydrogen. The constituents of bi-carburetted hydrogen are, 2 hydrogen and 2 carbon = 1 bi-carburetted hydrogen. In weight, 2 hydrogen and 12 carbon, or 2 + 12 = 14 bi-carburetted hydrogen.

These are the two principal gases which require attention, and as the oxygen of the air is an element that cannot be dispensed with, the object of our next inquiry will be into the quantity and constituents of atmospheric air.

According to the best authorities, atmospheric air is found in the proportion of 1 oxygen and 2 nitrogen, or, according to Mr. Williams (adopting the figures as representing the weights as before):—

Atmospheric Air.



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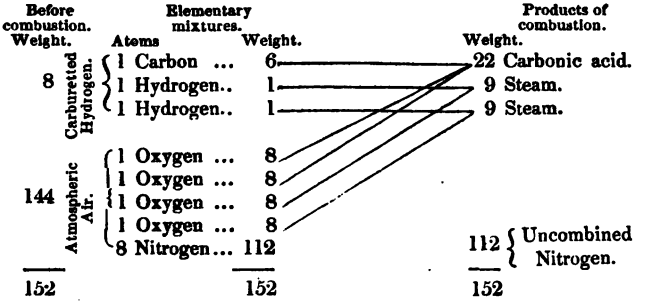
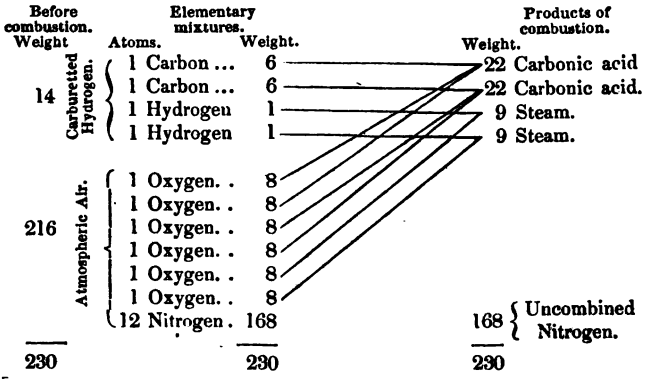
Having thus ascertained the constituents and equivalents in which the combustible and incombustible gases combine, it will easily be determined what quantity of atmospheric air will be necessary to support and effect perfect combustion of the fuel of which the above are constituents. For this purpose it will be observed that a very considerable quantity of air must be brought in contact with the incandescent fuel, before the process of combustion can be effected; and having already determined the constituents of each, we must next determine the quantity of air required for the purpose of supporting the entire combustion of the gases, without producing a diminution of the temperature in the process.

On this part of the subject several able authorities may be quoted; but taking that of Professor Brande (as given by Mr. Williams), the following diagram indicates the relative weights of the atoms both before and after combustion :—



Again, for the olefiant gas, or bi-carburetted hydrogen, we have :—



From the above it must appear obvious that in every instance of combustion the nitrogen or azotic gas (which forms so great a proportion of atmospheric air) is double the volume and three and a half times the weight of the oxygen, and being in itself incombustible, is absolutely of no use either as a combustible or supporter of combustion. On the contrary, it is exceedingly injurious, as not combining with the other gases; it reduces the temperature, and thus deprives the fuel of a great portion of its heat, which otherwise would (as in the case of the Bude light) have given much greater intensity of heat, and greater brilliancy

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in its illuminating powers. Finding it, however, impossible to separate the nitrogen from the oxygen of the air, (for general purposes), we must take the mixture as it is, and instead of using 1 atom of oxygen, we must take 2 of nitrogen along with it; and as 4 atoms of oxygen and 8 of nitrogen are required for the saturation of 1 atom of carburetted hydrogen, it follows that four times the quantity of air in volume, and 144 of weight, will be necessary for that purpose. Again, for the saturation of 1 atom of bi-carburetted hydrogen, 6 atoms of oxygen and 12 of nitrogen, in weight 216, are wanted, which, added to the previous quantity in combination with the carburetted hydrogen, the whole supply of air will therefore be $4 + 6 = 10$ volumes of atmospheric air to one of coal-gas. Ten to one is, therefore, the true proportion of atmospheric air required for attaining perfect combustion, and for reducing the gases to their ultimate products of carbonic acid and water.

Having determined the conditions and relative proportions of the gases and their supporters in a state of perfect combustion, it will be seen that in order to ensure economy and effect in the combustion of fuel, a large and copious supply of air must be admitted to the furnace, and that in the ratio of 10 volumes of air to 1 of coal gas. It is difficult to determine the exact quantities evolved from every description of fuel, and probably equally so to supply its equivalent of air; but in order to attain certainty in this respect, let the openings be made sufficiently large, and by a little attention to the quality of the fuel and quantity of air required for its combustion, the apertures may be contracted till such time as a mean average and a close approximation to the maximum effect are obtained.

The *Concentration of Heat* is a consideration of much importance in the economy of the steam-engine and the industrial arts; and as much depends upon its preservation, it may be useful in this place to direct attention to a few self-evident facts, which, if properly attended to, will lead to considerable saving in the use and application of heat.

It cannot be doubted that, after having applied the rules, conditions, and proportions requisite for the creation of heat, the whole of our knowledge may become obsolete unless the heat thus generated be closely preserved, and, if I may use the expression, *kept warm*. It would be worse than useless to study economy in one department, so long as a lavish expenditure goes on in another; and having once acquired a given quantity of heat, the next thing to be done is to retain and prevent its escape. Caloric is a body which radiates in all directions, and, unless surrounded with warm clothing or non-conducting substances, it is sure to disappear: and, although tightly bottled up, it sets at defiance the closest and hardest metals, and frequently escapes through the pores of the thickest iron and steel. Unlike gases and fluids, such as air and water, it is only kept within bounds by an envelope of soft wool or pounded charcoal, and the highest temperature of heat may sometimes be retained by a solid compact mass of lime and baked clay. This is strongly exemplified in the construction of ovens and furnaces, which, taken as a rule, will establish the principle on which heat can be preserved without diminution till it is used. For this purpose we should recommend the flues and furnaces of boilers and other fires to be closely encased with good building material adapted for the retention of heat, and all steam-boilers to be well covered and clothed, so as to prevent (as much as possible) the escape of heat in that direction; and for steam-engines, that all the steam pipes, cylinders, &c., should be closely enveloped in a thick coating of felt, canvass, or wood, and afterwards well painted. These precautions being taken, the effects will soon become visible in a saving of 15 to 20 per cent. of fuel.

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On the Prevention of Smoke.

The ultimatum of this inquiry is two-fold; first, the combustion of fuel; and secondly, the prevention of smoke. In the preceding investigation we have endeavoured to establish the laws which regulate and govern the combustion of fuel, and in that attempt we have also endeavoured to show the difference between perfect and imperfect combustion. Now, perfect combustion is the *prevention of smoke*, and whenever smoke makes its appearance, we may reasonably infer that there is imperfect combustion, and, probably, want of attention to a few simple rules is the cause. We have already inculcated these rules, and shown, from well-known chemical facts, that 1 atom of coal gas requires 10 atoms of atmospheric air for its complete combustion; *when that quantity is at its maximum or in excess, there is no smoke; when it is different, smoke is invariably present.* It therefore follows that, in order to render the residue of the products of combustion transparent or "*smokeless*," a supply of air, amounting to ten times that of the gases evolved, must be admitted. Should it exceed that quantity, the effect will not be smoke, but an additional expenditure of fuel to supply the loss of heat which this excess of air would require for absorption, rarefaction, &c. Hence the necessity which exists for power to regulate the admission, if not the exact, at least of an approximate quantity, of air. On the other hand, should the supply be deficient in quantity, (which is often the case), a dense volume of smoke is then visible, accompanied with all the defects and annoyances of imperfect combustion.

The variable changes which accompany perfect and imperfect combustion are not only visible, but may be proved by experiment. Let any person apply his hand to the tube of an Argand gas-burner, and he will find that the instant the aperture is partially closed, the flame immediately becomes elongated, and instead of a clear brilliant light, a dull red flame, with a dark volume of smoke, is the result. This shows the effect of a diminished supply of air; and the same may be applied to a steam-engine furnace, when imperfectly supplied with oxygen, when the gases pass off in opaque volumes unconsumed, and where a considerable portion of heat is entirely lost from that cause. It has been stated that we cannot have fire without smoke; but this is not the case in steam-boilers, as a well-constructed furnace, properly managed, furnishes many examples where bituminous coal is consumed in large quantities, and with little, if any, appearance of smoke. If coal were double the price, it is more than probable that a great improvement would shortly present itself, and that not exclusively in the suppression of the smoke nuisance, but in a further extension of those duties wherein economy becomes a leading feature in the attainment of these objects. It is, therefore, futile to urge difficulties which have already been overcome, and where, in many instances, "the prevention of smoke" is accomplished with perfect ease, and with great benefit to the parties concerned. In attempting the total suppression of this nuisance, two important considerations require to be attended to as essential; the first of which is *abundance of boiler space*, and the second a *sufficient supply of air*. For the last of these we have already given sufficient instructions for its admission; and for the first we could not furnish a better rule for the capacity and power of boilers than that which applies to the steam engine, namely, that of raising 33,000 lbs. one foot high in a minute. For example, suppose a steam-engine of 50 horse nominal power to be worked according to the indicator up to 80 horse, which, taken at 33,000 lbs. one foot high in a minute, we have then to calculate, from data already given, the size of boilers required. Using these precautions, and never loading the steam-engine beyond its nominal power without enlarging the boilers in proportion, the effects will be an almost total suppression of smoke, and a saving of fuel.

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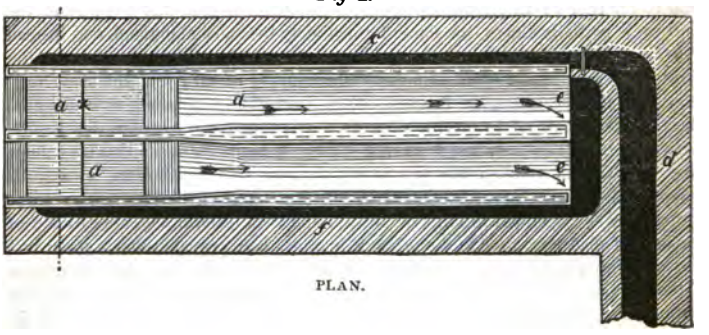
To all those practically acquainted with the subject, it is well known that a boiler of limited capacity, when overworked, *must be forced, and this forcing is the gangrene which corrupts and festers the whole system of operations.* Under such circumstances perfect combustion is out of the question, and any attempt at economy is, as heretofore, a complete failure. I have been the more particular on these points from having witnessed innumerable errors and mistakes in this respect, and it cannot be too forcibly impressed upon the minds of the public, that a LARGE BOILER is one of the essentials absolutely necessary for the acquirements already insisted upon.

IMPROVED STATIONARY BOILER.

Fig. 1.

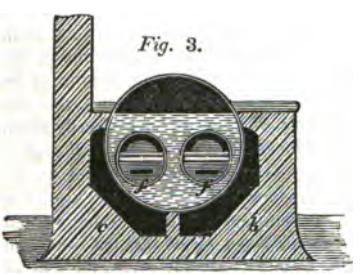
SECTIONAL ELEVATION.

Fig 2.



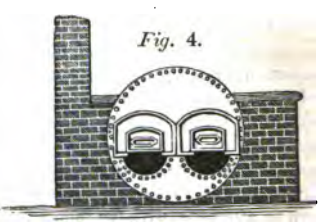
PLAN.

Fig. 3.



SECTION AT A B.

Fig. 4.



FRONT OF BOILER.

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Description.—Figs. 1 and 2 represent a plan and longitudinal section of the boiler, with double flues and double furnaces, and *Figs* 3 and 4 a transverse section and end view. In these representations it will be seen that the gases emitted from the furnaces *a*, *a* ×, are conducted along the internal tubes into the return flue *b*. From *b* they cross under the boiler below the ash-pit into the flue *c*, and from thence along the opposite side of the boiler into the main flue *d*, which communicates with the chimney. From this description it will be observed that the gases do not unite until they have reached *e e* at the end of the boiler. At this point a change immediately takes place in the gaseous products, and that from one of two causes, as follows: suppose the furnace *a* × to be newly fired, and the fuel in it in a perfectly incandescent state, it then follows that the gases passing from *a* will not only be different in their constituents to those from *a* ×, but they are at a much higher temperature; and both furnaces having received air as a constant quantity through the fixed apertures *f f*, it will be seen that, in the event of a surcharge of air on one side and a diminished supply on the other, that their extremes are neutralized by the excess of oxygen thus introduced, and the increased temperature which effects ignition at the point *e*, where combination takes place. All that is therefore necessary is to replenish the fires alternately every twenty minutes, in order to effect the combustion of the gases without the least appearance of smoke. These, and the increased recipient surface, are the leading properties of this boiler, which, compared with others having single flues, is found to be greatly superior either as regards the combustion or economy of fuel.

General Summary of Results.

In briefly recapitulating the experiments, observations, and results obtained, it will be seen that in the procurement and employment of heat, a number of important matters have to be considered.

1st. The quality and properties of the fuel used.

2nd. Its treatment in the furnace, and the supply of air requisite for its combustion.

3rd. The form of boilers, and the extent of their absorbent surfaces.

4th. The concentration and economy of heat. And

Lastly. The prevention of smoke.

These have been treated upon in their respective order, and all that now remains is to collect them into form, and draw such conclusions as will enable practical men to understand and apply the means necessary for their fulfilment.

From what has been stated, and from the many facts collected and experiments made, it will appear conclusive that a much better and more comprehensive system of combustion can be accomplished; and by attention to the following results, great and important advantages may be obtained.

Amongst the varied species of fuel enumerated in the foregoing experiments, there will be found ten different sorts of coal, each exhibiting its peculiar properties and compounds. For the sake of brevity and deduction, these may be divided into three kinds, namely, the anthracite, the bituminous, and splint qualities. Of the anthracite we have little experience beyond a knowledge of its properties and the absence of smoke. It is a coal which requires a large supply of oxygen for its combustion, and instead of the furnace usually employed for the consumption of the bituminous kind, it would require one possessing the power of a reverberatory or a strong blast acting upon it, and that under circumstances of a minute division of its parts.

The bituminous kind is, however, what we have most to do with, and on reference to its constituents, it will be seen that a specific quantity of atmospheric

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air is absolutely necessary for its combustion, amounting, as already stated, to ten times the volume of gases it contains. Now, from a number of well-conducted experiments on the waggon-shaped, and the improved boilers with double flues, it was ascertained that the following proportions of permanent openings for the admission of air behind the fire bridge were the nearest approach to perfect combustion.*

SUMMARY OF RESULTS, obtained from seventeen experiments with fixed apertures for the admission of air behind the bridge, of two 40-horse power boilers.

Description of Boilers and number of Experiments made.	Power of Boilers in horses.	Area of grate-bars in feet.	Area of permanent aperture in square inches.	Number of square inches of aperture to every foot of grate-bar.
Waggon boiler, mean of 10 experiments	40	28.0	46.3	1.64
Double furnace boiler, mean of 7 experiments	40	23.4	18 5	.46
Mean.	40	25.7	32.4	1.05

It therefore appears that about 26 square feet, and 32½ inches of permanent aperture for the admission of air, is the mean of the old and improved boilers.

This proportion must not, however, be taken as a criterion for every boiler, as much depends upon the principle on which they are constructed; and it will be safer to adopt the mean results of the experiments as shown in the table, than to apply them without exception to every description of boiler and furnace. Taking therefore the mean of the whole experiments, we may safely administer the following supply of air behind the bridge.

For cylindrical, waggon-shaped, and every description of boiler of the usual construction, give permanent opening for the admission of air of 1¼ square inch to every square foot of grate bar; and for every square foot of grate bar surface in the double-furnace and double-flued boiler, give half a square inch, or .5 for the same purpose.

Practically considered, this will be found a near approximation to the correct quantity of air required for the support of effective combustion in each; and provided necessary attention is paid to considerations involving the consumption of bituminous coal, of different kinds, we may reasonably infer a greatly improved process in the use and absorption of our mineral fuels.

In the combustion of splint and slaty coal, a different treatment will be required as respects either the anthracite or the bituminous kinds; the one is obdurate and hard, the other is compact, and in some instances liquefies like pitch.

* It is due to Mr. John Wakefield (formerly of Manchester, now of Farnworth, near Bolton) to state, that he was amongst the first who turned his attention to the admission of air at the bridge, behind the furnace, for the purpose of consuming the smoke as it escaped into the flues. His first furnace was constructed on a plan of his own, having a hollow bridge closed at the top, and thus rendering it an air chamber connected with openings on each side of the furnace. On this plan the air was heated by the passing currents, and by a communication from the air chamber to an opening in the arch plate over the furnace door; the air thus rarefied was forced downwards, by the form of the opening in the plate, direct upon the fire. A variety of other schemes were tried by Mr. Wakefield, some of them successfully; and it is only justice to that gentleman to state, that a considerable portion of his life was devoted to improvements in steam boiler furnaces, and the abatement of a nuisance which at that period (nearly thirty years ago) was justly complained of.

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Now the splint and slaty specimens burn open and rapid, and therefore require less air, exclusive of what is taken through the grate bars.

In some cases it may, however, be necessary to overtake and effect the ignition of such gases as may escape over the bridge unconsumed, and for this purpose, in some descriptions of light coal, it may be desirable to admit about half the quantity of air used in the combustion of the bituminous kinds.

The ultimate results are, therefore,—

A perfect knowledge of the properties of the fuel used, and judicious management in working the fires.

An increase in the area of recipient surface of the boiler in the ratio of the furnace as 1 to 18; or what is the same thing, a reduction of the grate-bar surface to that proportion.

A constant supply of air (through a fixed aperture) of $1\frac{1}{4}$ square inch to every foot of grate-bar in common boilers, when burning bituminous coal; and half that area when using splint coal. These openings should, however, be regulated, in the first instance, by hand, until the mean or maximum effect in reference to the fuel is obtained.

A complete covering of felt, or some other non-conducting substance, to be applied to the exterior parts of the boiler, and the flues to be well protected on all sides from the external air.

On a strict observance of these rules will depend the question of *smoke* or *no smoke*, and also whether an important economy in the use of fuel shall or shall not be effected. We are assured, from the experimental facts already recorded, that both these objects can be accomplished, and it rests with the community to determine how far they shall be carried into effect.

At the time of entering upon this investigation, it was my intention to have confined it within exceedingly narrow limits: it was, however, found to increase in interest as I advanced; and from the nature of the subject, and the number of considerations connected therewith, I became involved in a long and important inquiry; an inquiry progressively developing new features, and admitting of no curtailment except only in such matters as did not directly bear upon the subject. As it is, I fear I have but imperfectly discharged the duty entrusted to my care: it is, however, done honestly; and trusting to future developments in the hands of superior writers, I close the report under the impression that the preceding investigations may direct public attention to the extension of our knowledge and improvement of our practice in the combustion of fuel and the prevention of smoke.

Manchester, Nov. 30, 1844.

NOTE BY MR. FAIRBAIRN, BEING AN APPENDIX TO THE PRECEDING REPORT.

During the progress or about the close of the above report, I found that my friend and former pupil, Mr. A. Murray, had communicated a paper on a similar subject to the Institution of Civil Engineers, entitled, "The construction and proper Proportion of Boilers for the Generation of Steam."

Mr. Murray has had many opportunities of judging of the best forms and proportions of marine boilers, and, from the facilities afforded in his professional avocations at the Royal Dockyard, Woolwich, I am induced to quote a few of his observations relative to the area of the flue, bridge, chimney, &c., which have in some degree been omitted in the preceding report. In treating of the quantity of air entering into combination with the volatile products of pit coal, Mr. Murray states, that "The quantity of air chemically required for the combustion

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of 1 lb. of coal has been shown to be 150.35 cubic feet, of which 44.64 enter into combination with the gases, and 105.71 with the solid portion of the coal. From the chemical changes which take place in the combination of the hydrogen with oxygen, the bulk of the products is found to be to the bulk of the atmospheric air required to furnish the oxygen, as 10 is to 11. The amount is, therefore, 49.104. This is without taking into account the augmentation of the bulk due to the increase of the temperature. In the combination which takes place between the carbon and the oxygen, the resultant gases (carbonic acid gas and nitrogen gas) are of exactly the same bulk as the amount of air, that is, 105.71 cubic feet, exclusive, as before, of the augmentation of bulk from the increase of temperature. The total amount of the products of combustion in a cool state would, therefore, be $49.104 + 105.71 = 154.814$ cubic feet.

"The general temperature of a furnace has not been very satisfactorily ascertained, but it may be stated at about 1,000° Fahrenheit, and at this temperature the products of combustion would be increased, according to the laws of the expansion of aëriform bodies, to about three times their original bulk. The bulk, therefore, of the products of combustion which must pass off must be $154.814 \times 3 = 464.442$ cubic feet. At a velocity of 36 feet per second,* the area, to allow this quantity to pass off in an hour, is .516 square inch. In a furnace in which 13 lbs. of coal are burnt upon a square foot of grate per hour, the area to every foot of grate would be $.516 \times 13 = 6.708$ square inches; and the proportion to each foot of grate, if the rate of combustion be higher or lower than 13 lbs. may be found in the same way.

"This area having been obtained, on the supposition that no more air is admitted than the quantity chemically required, and that the combustion is complete and perfect in the furnace, it is evident that this area must be much increased in practice where we know these conditions are not fulfilled, but that a large surplus quantity of air is always admitted. A limit is thus found for the area over the bridge or the area of the flue immediately behind the furnace, below which it must not be decreased, or the due quantity could not pass off, and, consequently, the due quantity of air could not enter, and the combustion would be proportionally imperfect. It will be found advantageous in practice to make the area 2 square inches instead of .516 square inch. The imperfection of the combustion in any furnace, when it is less than 1.5 square inch, will be rendered very apparent by the quantity of carbon which will rise unconsumed along with the hydrogen gas, and show itself in a dense black smoke on issuing from the chimney. This would give 26 square inches of area over the bridge to every square foot of grate in a furnace in which the rate of combustion is 13 lbs. of coal on each square foot per hour, and so on in proportion for any rate. Taking this area as the proportion for the products of combustion immediately on their leaving the furnace, it may be gradually reduced as it approaches the chimney, on account of the reduction in the temperature, and, consequently, in the bulk of the gases. Care must, however, be taken that the flues are nowhere so contracted, nor so constructed, as to cause, by awkward bends or in any other way, any obstruction to the draught, otherwise similar bad consequences will ensue."

From this statement it would appear that 26 square inches of area over the bridge is about the correct proportion for the combustion of 13 lbs. of coal per hour on each square foot of grate-bar. Now these proportions are rather more than are given in stationary boilers, as the mean of a number of experiments, taken where the combustion was most perfect, gave about 18 square inches over the

* See Dr. Ure's experiments, read before the Royal Society, June, 1836.

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bridge, and about 28 square inches as the area of the flues to every square foot of grate-bar.

These data may not at first sight appear important; they are, however, of great value in practice, as the economy of the fuel and the efficiency of the furnace in a great measure depend upon the height of the bridge behind, which operates as a retarder of the currents, in the same way as the damper is used for checking the draught of the chimney in the flues.

Mr. Murray further treats of the temperature of the furnace, flues, &c., but these points having already been experimented upon and fully discussed in the report, it will not be necessary to notice them in this place.

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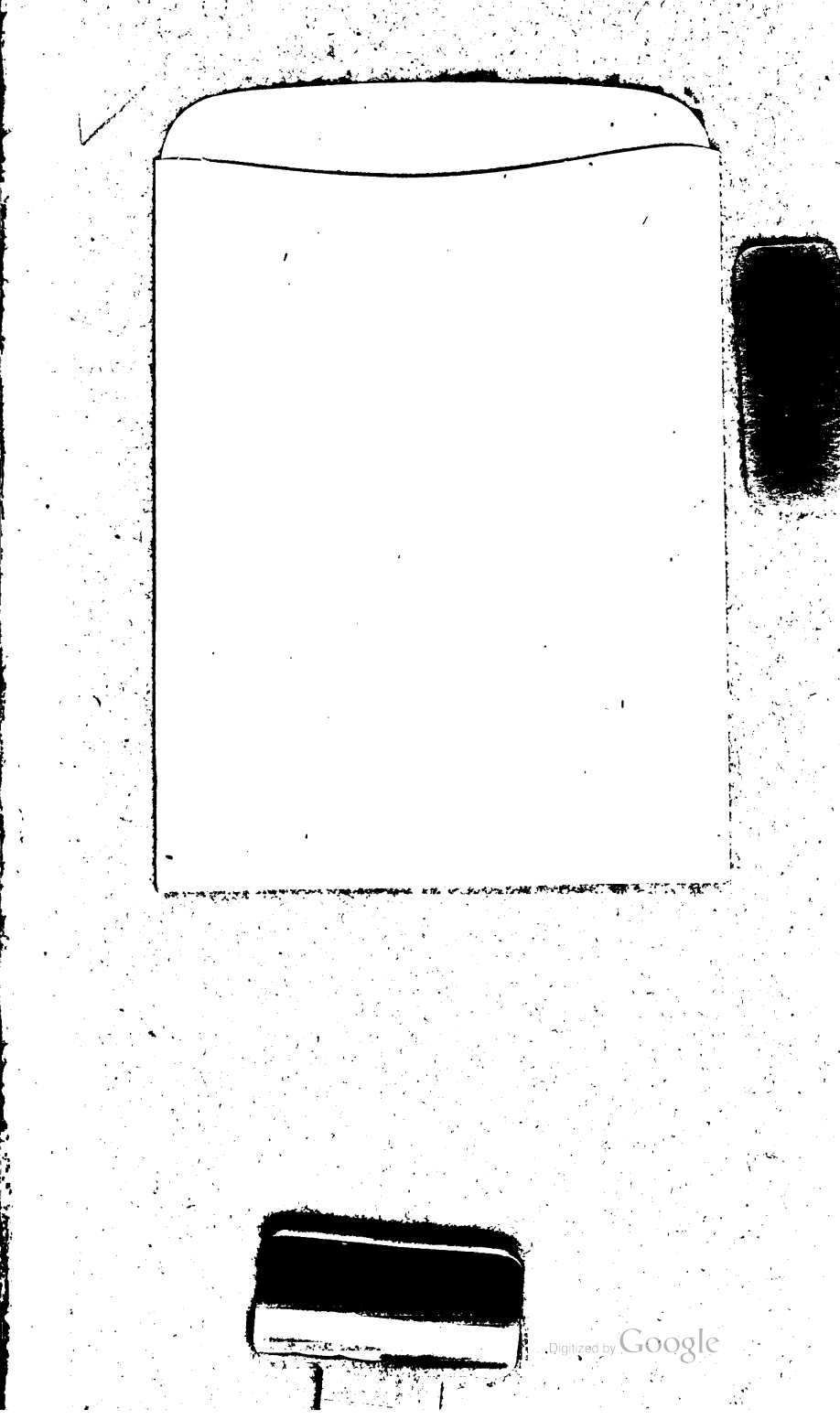
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